EVALUATION OF POTENTIAL WASTE HEAT RECOVERY OPPORTUNITIES FROM THE BOILER CONTINUOUS BLOWDOWN SYSTEM IN LAKVIJAYA POWER STATION

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Degree of Master of Engineering

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ABSTRACT

An evaluation of potential waste heat recovery opportunities from boiler continuous blowdown system in Lakvijaya coal power station was carried out to assess the waste heat availability, recovery methods and introduced a mathematical model for energy extraction per unit capital cost for the proposed energy recovery system. Calculated total waste heat availability from all three boilers in the power station varies from 3,950 kW to 11,851 kW, when boiler continues blowdown rate changes from 10,250 kg/h to 30,750 kg/h. Two possible opportunities to recover waste heat have been identified. They are considered for working as a heating fluid for heat exchanger to heat up condensate water and the other as a heat source for vapour absorption chiller for partially or fully replace currently use electrically driven vapour compression air conditioning chillers having total cooling capacity of 2,500 kW. Proposed new layout for boiler blowdown system with new components include a heat exchanger and an absorption chiller. The consequently analysed energy system is in terms of energy extraction and energy extraction per unit capital cost by varying heat exchanger outlet waste heat fluid temperature and boiler continues blowdown rate. A regression model was developed to heat exchanger capital cost by using Minitab statistical software and required cost data to build a model was taken from CAPCOST ver2 software. From the results it is observed that energy extraction per unit capital cost is optimum at heat exchanger outlet temperature in between 120 ^{0}C to 95 ^{0}C, where affect from absorption chiller was insignificant and result was similar in both single stage and two stage chiller machines. Two regression models were developed for energy extraction for unit capital cost with four variables and R-sq values were 86.66% and 76.86% for two stage chiller and single stage chiller system respectively. This model can be used to find optimal points in similar applications.

Key Words: boiler waste heat recovery, continuous blowdown, condensate water preheating, vapour absorption chiller, capital cost estimation, energy extraction per unit capital cost, mathematical modelling, thermodynamic analysis, sensitivity analysis.

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LIST OF ABBREVIATIONS

BMCR	Boiler Maximum Continues Rating
CBD	Continues Blowdown
CEB	Ceylon Electricity Board
COP	Coefficient of Performance
ETS	Emergency Trip System
FDF	Forced Draft Fan
HP	High Pressure
IBD	Intermittent Blowdown
IDF	Induced Draft Fan
IP	Intermediate Pressure
LP	Low Pressure
LVPS	Lakvijaya Power Station
PAF	Primary Air Fan
PVC	Pressure Variable Control
TDS	Total Dissolved Solids
TSI	Turbine Supervisory Instrumentation
UK	United Kingdom
USA	United States of America

1 INTRODUCTION

1.1 Background

Lakvijaya coal power station contributes over 50% (www.ceb.lk) of the total electric power generated in Sri Lanka when all three units are at full load operation condition and is responsible for highest fossil fuel related greenhouse gas emissions in power sector. It is estimated that about 60% (New Coal Fired Plant Performance and Cost Estimates, 2009) of fuel energy input is lost as waste heat in the form of hot exhaust gases, cooling water, boiler blowdown, and heat lost from hot equipment surfaces and steam leakages etc. In the present context, industrial sector maximize their efforts to improve its energy efficiency by recovering waste heat losses and those efforts are provided an attractive opportunities for an emission free and less costly energy resource.

Waste heat recovery from exhaust flue gases is usually practiced in many instances rather than other areas having significant potential to recover waste heat, especially from the boiler blowdown water in large coal fired power stations. The boiler blowdown process involves the periodic and/or continuous removal of heated and pressurized water from the steam drum of a boiler to control salinity of boiler water and remove accumulated dissolved solids. During this blowdown process, water is discharged to prevent negative impact to boiler from dissolved solids or salinity which can cause for boiler efficiency and frequent maintenance. However, the boiler blowdown results in waste of energy, because the blowndown water is at higher thermal conditions as the values of boiler saturated steam produced. Although there is one method available to recover the flash steam from blowdown, there are more than 50% (Enthalpy of CBD waste heat at LVPS) of blowdown water discharge without waste heat recovering.

1.2 Problem statement

Boiler blowdown system is running with significant waste heat in 3X300 MW_e coal power station by creating many opportunities which are available to use as an energy source for new LP heater which can be used to heat condensate water and vapour absorption refrigeration system for air conditioning requirements. Boiler blowdown system of one unit is continuously discharge saturated water form steam drum with 1% of BMCR load as a manufacturer's recommendation. As a result each unit continuously discharge saturated water around 17.0 MPa pressure and 353 ^{0}C temperature by 10,250 kg/h rate to CBD flash tank. CBD flash tank is operating around 1.4 MPa, 198 ^{0}C with saturated water and steam which can be recovered 4,473 kg/h flash steam to deaerator as 43.64% of total. Remaining balance of saturated water at 1.4 MPa pressure and 198 ^{0}C is discharged to IBD flash tank by 5,777 kg/h rate without energy recovering.

The aim of this research project is waste heat recovery in Lakvijaya coal power station from boiler CBD system in terms of optimum energy extraction per unit capital cost.

1.3 Objectives

The objectives of the research are given below.

- Identify energy losses, energy saving opportunities and assessment of the past and current development for waste heat recovery from boiler blowdown water based on coal fired power generation.
- Find the potential of waste heat availability from boiler blowdown system.
- Find available opportunities in Lakvijaya coal power station to recover, using waste heat recovery technologies.
- Analyse of the collected data for waste heat recovery by combining two or more opportunities as availability of waste heat.

2 LITERATURE REVIEW

2.1 Sri Lankan context of coal fired power generation

2.1.1 Brief Introduction of Lakvijaya Power Station (LVPS)

Lakvijaya Power Station (LVPS) is the first ever coal based power plant in Sri Lanka. This plant is a “Base Load” power plant and currently it contributes 900 MW, which is approximately 40% (Considering peak load 2200 MW- 1800hrs. to 2200 hrs.) of national power requirement of Sri Lanka. Main contractor of the power plant was China Machinery & Engineering Corporation. The Power plant is managed by Ceylon Electricity Board, a state owned electricity company. It is located at Narakkaliya, Norochcholai village in Kalpitiya Peninsula, North Western province.

2.1.2 Overview of Boiler

Characteristics and specifications for boiler equipment

The boiler (HG-1025/17.3-YM25) is steel-frame suspension structured, bituminous coal fired drum type with sub-critical parameters. Main features of the boiler are natural circulation, single furnace, intermediate reheat, balanced draft, corner firing, tangential firing, and dry ash conveying. The whole boiler is arranged showing as a reverse "U shape, with a fixed expansion centre. The membrane wall and its upper furnace arch form the furnace and the rifled tubes are used for high heat load zone in the water wall. The wall reheater, isolating platen, rear plate superheater are arranged in upper part of the furnace. The rear panel reheater, final reheater and final superheater and vertical low-temperature superheater are arranged in the middle part of a horizontal flue along the flow direction of flue gas. A horizontal low-temperature superheater and an economizer are arranged in the shaft of rear pass and 3-compartment two rotary air preheaters are arranged in the lower part of the rear pass.

Superheated steam temperature is regulated by two stage spray water system and reheated steam temperature is regulated by both tilting burner as well as spray water system.

Table 2.1: Boiler main parameters

Description	**Units**	**Value**
Firing mode		Quadrangle tangential firing
Air flow		Balanced draft
Temperature control mode		De-superheating water for super heaters in two stages. Sway burner and single stage de-superheating water for reheaters
Operation modes		Fixed / Sliding pressure modes
Rated evaporation capacity	t/h	912
Outlet pressure of superheated steam	MPa	17.3
Temperature of superheated steam	℃	541
Inlet/outlet pressure of reheating steam	MPa	3.993/3.793
Reheating steam flow	t/h	851.3
Fuel consumption	t/h	110.4
Circulating water flow	t/h	42800
Guarantee/calculated thermal efficiency	%	93.35/92.8
Furnace dimensions (Width×Depth)	m	14.048 × 11.858
Chimney height	m	150.0

2.1.3 Overview of Steam Turbine

The N300-16.7/538/538 Turbine manufactured by Harbin Steam Turbine Plant based on the technology of 300 MW reference unit from Westinghouse Electric, which is new turbine with improved technology. Main features of the turbine are sub-critical, primary intermediate reheat, single-shaft, double cylinder, double exhaust, reaction type with single stage impulse and condensing steam turbine.

Table 2.2: Turbine main parameters

Description	Units	Value
Rated main steam pressure	MPa.g	16.7
Rated main steam/ reheat steam temperature	℃	538/538
Rated HP cylinder exhausting outlet pressure	MPa.a	3.602
Rated main steam inlet flow rate	t/h	907.81
Rated exhausting pressure	MPa.a	0.007
Designed cooling water temperature	℃	28
Rated rotating speed	rpm	3000
Blade length of LP last stage	mm	900
Number of stages in HP/IP/LP cylinders	stage	I+12/9/2x7
Maximum back pressure value	MPa.a	0.0186
Maximum exhausting temperature	℃	121
maximum continuous load	MW	315
Guarantee net heat rate	kJ/kWh	7920

2.2 Energy losses in coal fired power plants

Pulverized coal fired boilers are usually operated with total losses about 12% to 14% and this significant amount is influenced to limit the boiler efficiency from 86% to 88% for continuous operation. However, 50% of the total losses can be tuned and optimize by controlling carbon loss and flue gas loss and other half of losses are counted by fuel properties such as, amount of hydrogen in fuel, moisture content in fuel, ambient air conditions, blowdown loss and other minor losses.

2.2.1 Carbon loss

Carbon losses are occurred due to partial combustion of coal powder in furnace and this is usually visible as an unburned carbon in fly ash and bottom ash in the boiler. Large size of unburned particles are discharged with bottom ash because higher specific gravity having the unburned materials and small size unburned particles are discharged with fly ash and it will be create a quality issue of fly ash, if it is used for cement or roofing productions as a row material. Main factors affected the carbon losses are,

- Rank and quality of the coal
- Petrographic characteristics of coal
- Characteristics and quantum of carbonaceous shale
- Presence of low melting point inorganics in coal ash
- Available residence time for combustion
- Type of the burners
- Number of burners
- Type of pulverizing system
- Primary air control system of coal pulverisers
- Fineness of pulverised coal powder
- Ratio between Primary air to secondary air
- Excess air at the furnace and distribution of air into the furnace
- Burner Tilt angle

2.2.2 Flue gas loss

Flue gas loss accounts around 40% of total energy losses in the boiler and which is due to the heat carried away by the flue gases leaving the boiler. Nowadays, boiler designers are minimizing flue gas losses by recovering heat after the low temperature super heaters in order to adding compatible economizers and air pre heaters. Flue gas loss can be reduced by maintaining following factors at optimum conditions and operator experiences are key factor to control boiler at these conditions.

- Control excess air at optimum level

- Tune combustion of coal to the optimum condition
- Proper distribution of combustion air
- Maintain fineness of pulverized coal powder
- Maintain pulverisers outlet temperature as maximum possible level to reduce bypass amount of air in air pre-heater
- Conducting boiler soot blowing for the entire heat transfer surface at an optimal frequency
- Minimize the possible air leakages to the boiler

2.2.3 Losses due to boiler blowdown

Boiler feed water usually contains some amount of impurities, such as suspended impurities, dissolved solids and salinity, although there are acceptable pre-treatment methods are in operation. Impurities can be accumulated inside the boiler during continuous operation and further increased concentration of dissolved solids is influenced to carryover those impurities into the steam, causing damage to pipes, fittings and process equipment. The increasing amount of suspended solids can be form sludge, which can be influenced to weaken the both boiler efficiency and heat transfer capability.

Therefore, boiler water should be intermittently discharged to regulate the concentrations of both suspended and total dissolved solids (TDS) to safe, reliable and optimum operation of the boiler. Surface water discharge (blowdown) should be usually done by continuous basis to reduce the concentration level of dissolved solids and bottom water discharge (blowdown) should be done by periodic basis to remove sludge from the bottom of the boiler. Improper boiler blowdown can be influenced to high fuel consumption, further chemical treatment requirements and heat loss. In addition to that, blowdown water is consist with same temperature and pressure as the boiler water and that heat can be recovered to reused. Benefits of the boiler proper blowdown can be listed as follows.

- Reduce consumption of fuel, water and chemicals
- Low maintenance cost which is related to carryover and deposits

- Availability of supervision using automatic control
- Clean and efficient steam supply
- Low operating cost due to reduction in consumption, disposal, treatment and heating of water
- Reduce energy loss from boiler blowdown

Since measure the TDS in the boiler water is time consuming, conductivity measurement is used to monitor the TDS level in the boiler. Therefore, increase in conductivity value indicates an increase in the impurity concentration. Conventional methods for discharge the boiler water is depend on two kinds of blowdown systems, called intermittent and continuous blowdown.

Intermittent Blowdown (IBD)

The intermittent blown down is related to water discharge from the lowest point of the boiler shell to control parameters, such as TDS or conductivity, PH, Phosphates concentration and Silica within recommended limits so that steam quality is maintained at qualified condition. During the IBD process, water discharged from boiler in high rate for a short period of time and the time is based on a thumb rule called “once per shift for 2 minutes”. During intermittent blowdown process, requires higher amount of feed water for short period and therefore, required higher capacity feed water pumps than CBD process required. In addition to that, TDS level of the boiler can be varied according to the fluctuations of the boiler water level, because changes in size of steam bubble and their distribution which proportional to the changes in concentration of dissolved solids. Also considerable amount of heat energy is losing with IBD and it is designed to remove suspended solids including any sludge formed in the boiler water.

The IBD discharge is usually located in the bottom of the bottommost boiler drum or header, where any sludge/scale formed can be tend to settle. Properly controlled IBD system can remove suspended solids, allowing satisfactory boiler operation. Most industrial boilers contain both IBD and CBD systems. In practice, the IBD valves are opened periodically in accordance with an operating sequence. Frequent short IBD discharges are preferred than random lengthy discharges in terms of both optimize removal of suspended solids and operating economy. The IBD can be carried out less frequency than other systems, which are having contaminated feed water with hardness or iron. IBD valves on the boiler water wall headers should be operated according to guide lines of the manufacturer. The boiler water level should monitor closely during periods of IBD.

Continuous Blowdown (CBD)

As per the term indicate of CBD, which is continuous removal of water from the boiler at operation condition. CBD have many advantages which are not provided by IBD process. According to the design of CBD system, water removed from the location of highest concentration of dissolved solids in the boiler water. As a result, quality of the boiler water can be maintained continuously. Also, significant amount of dissolved solids can be removed with low loss of water and heat from the boiler. In addition to that, significant amount of CBD flash steam can be recovered through blowdown flash vessel and heat exchangers. Control valve settings should be adjusted according to control test results in order to maintain the boiler water concentrations continuously. When CBD is used, IBD should be limited to approximately one short discharge per shift to remove suspended solids which can be settled out near the IBD pipe line.

2.2.4 Losses due to radiation and convection

Insulations of boiler surfaces and steam piping are key factor for these losses and therefore, insulations need to inspect for damage and replacement if required on a regular basis. The boiler surface easily loses heat energy to the surrounding environment which is relatively cool and these type of boiler losses are very high during the wind seasons.

2.2.5 Excess air control

Excess Air requirement for boiler is very important, because the complete combustion required range of excess air, which is depends on the type of fuel used. It is required to maintain the excess air at optimum level in order to reduce energy requirement to heat the excess air to flue gas temperature. In addition to that, thermal NOx formation is influenced at both high temperature and high excess air conditions and it is also affected to environmental pollution issues. Oxygen Analysers at flue gas outlet is helpful to maintain the excess air in the required level during normal operations of the boiler. However, excess air need to be controlled carefully during sudden load changes otherwise it is detrimental to the efficiency of the boiler.

2.2.6 Losses due to fuel quality

Moisture and Ash content in the fuel significantly influenced to loss of heat and it will decrease the boiler efficiency. These losses are caused due to heat requirement for evaporating the moisture in fuel and heating it to the flue gas temperature and which creates energy loss. Therefore moisture content of both fuel and combustion air should be controlled accordingly. In addition to that, Sulphur content of fuel also important as a quality of the fuel and increase in Sulphur level is directly influenced to increase the dew point. Therefore heat recovered from flue gas has to limit in order to prevent dew point corrosion of flue gas system. Ash content in the fuel is the other factor which is influenced to decrease boiler energy efficiency. Loss due to unburnt bottom ash and fly ash is unrecoverable part of the energy.

2.2.7 Losses due to incomplete combustion

Incomplete combustion results in Carbon Monoxide emission which is largely contributed for both the environment pollution and decrease the boiler efficiency. Particle size of the coal powder is an important parameter, which has to be controlled precisely in coal fired power stations. Motor power of coal pulverisers increase for very fine particles and too coarse particles results incomplete combustion with significant unburnt losses. Particle size should be optimized taking consideration of both issues. When considering Fuel oil fired boilers, proper atomization is needed from steam or air in order to better combustion efficiency.

2.2.8 Losses due to Scale and Soot Formation

Scaling is mainly occurred due to improper treatment systems inside water tubes in water tube boiler. Soot formation in coal and fuel oil fired boilers will increase thermal resistivity because of reduced effective heat transfer area and decreased thermal conductivity in a boiler. During shut down period of the boiler, it is possible to use both physical and chemical cleaning methods to restore the heat transfer effectiveness of the boilers. When considering normal operation period, proper soot blowing operation should be used to remove soot from the all heat transfer surfaces and which will leads to restore boiler efficiency.

2.2.9 Losses due to leakages

Leakage of primary or secondary air increases the motor power of the combustion air fan due to increment of volumetric flow requirement. Leakages of preheated primary or secondary air results energy loss in addition to loss of motor power. Flue gas leakages are influenced to both heat energy loss and surrounding environment pollution. Faulty air ingression in negative pressure regions creates dilution of hot air and it will increases fuel requirement. Both internal and external corrosion possibilities need to be periodically inspected and corrective action has to be taken to avoid reduction in boiler efficiency through possible leakages.

2.3 Energy saving opportunities from boiler blowdown system

Heat recovery is frequently used to reduce energy losses in any thermal system and waste heat recovery from boiler blowdown system shown in Figure 2.2. This Figure represent a typical boiler blowdown waste heat recovering opportunity using both flash tank and heat exchanger.

Installation of waste heat recovery system is significant, if that waste energy from either flash tank or blowdown water can be recovered and utilized. When an excess supply of exhaust or low-pressure steam is available, justification should be carried out in order to installing heat recovery equipment. If it is economically justified, boiler blowdown waste heat can be used to heat process streams. In modern coal fired boilers, blowdown heat recovery systems use flash steam from the flash tank for de-aeration. Then remaining balance of blowdown water in the flash tank can be directed through heat exchanger and used to preheat boiler makeup water. Heat loss can be minimized to loss from the terminal temperature difference between the inlet makeup water and the blowdown water final discharge with the use of an efficient heat exchange unit.

2.3.1 Heat recovery systems from boiler blowdown

In addition to appropriate blowdown practices associated with use of automatic blowdown control and reducing costs & heat losses, also can be recovered heat/energy in the blowdown water. Blowdown water has same temperature and pressure as the boiler water. Before this high-energy waste fluid is discharged, the resident heat in blowdown can be recovered through a flash tank, a heat exchanger, a vapour absorption chiller or the combinations. Any boiler with continuous surface water blowdown exceeding five percent of the steam generation rate is a suitable unit for blowdown waste heat recovery.

2.3.2 Flash Tank System

The flash tank waste heat recovery system shown in Figure 2.1 can be used with low expense and also system complexity will be reduced to a minimum. In this system, blowdown water from the boiler can be sent through a flash tank, which is able to generate low-pressure flash steam. This low pressure flash steam is typically used in de-aerator or makeup water heaters and these flash vessels are called CBD flash tanks and usually equipped in new coal fired power plants.

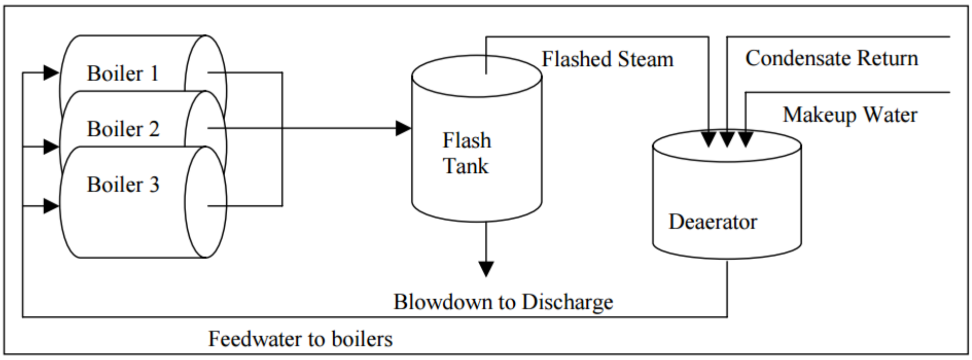


Figure 2.1: Schematic flash tank system for energy recovery

Source: Boiler blowdown by NCDENR, 2004

2.3.3 Flash Tank – Heat Exchanger System

Waste heat recovery system shown in Figure 2.2 is consisted with both flash tank and heat exchanger in series arrangement. The temperature of the blowdown leaving the flash tank is usually above 220 °F. The energy of this flash steam can be used to heat boiler makeup water using the heat exchanger, while cooling blowdown water. Preheating boiler makeup water is influenced to reduce fuel cost. In addition to that, cooling blowdown water in same time is helpful to fulfil requirements of local environmental codes and regulations, because discharge of high temperature liquids into the sewer system may be harmful.

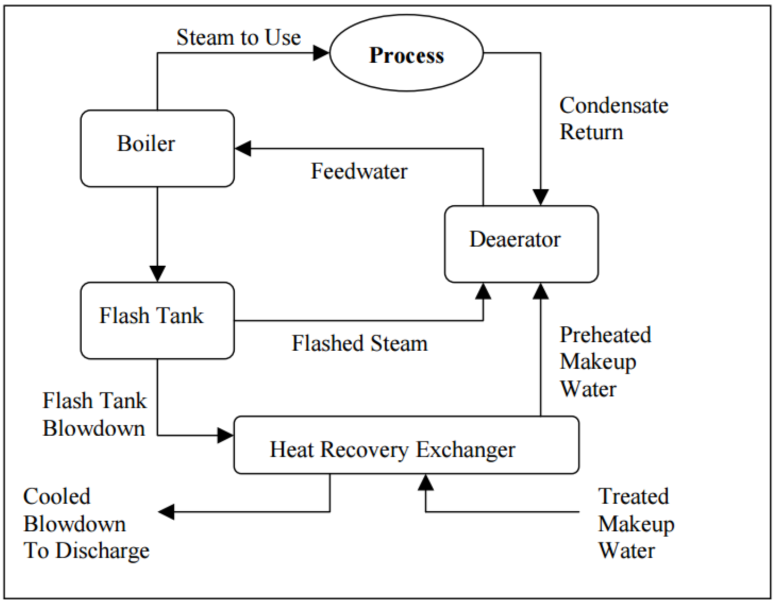


Figure 2.2: Schematic of flash tank heat exchanger system

Source: Boiler blowdown by NCDENR, 2004

2.3.4 Vapour absorption chillers

Vapour absorption chiller is a machine that can be generated chilled water based on heat source rather than electrical power which is used in vapour compression refrigeration systems. As same as in vapour compression cycle, absorption cycle completed by removing heat by evaporation of refrigerant at lower pressure and then discharge of heat by condensation of refrigerant at higher pressure. The major difference between a vapour compression and an absorption chiller systems is working energy source, which is supplied by compressor in compression system to make the pressure difference required to circulate the refrigerant while the absorption chiller using heat for that. The absorption system is very attractive in nature because of it uses energy in different forms of heat such as, solar or waste heat, makes it using a little work input and saving in money. Also it can works with industrial waste heat streams.

Absorption chillers can be either lithium bromide-water (LiBr/H_2O) or ammonia-water equipment systems. The LiBr/H_2O system uses lithium bromide as the absorber and water as the refrigerant. The ammonia-water system uses water as the absorber and ammonia as the refrigerant.

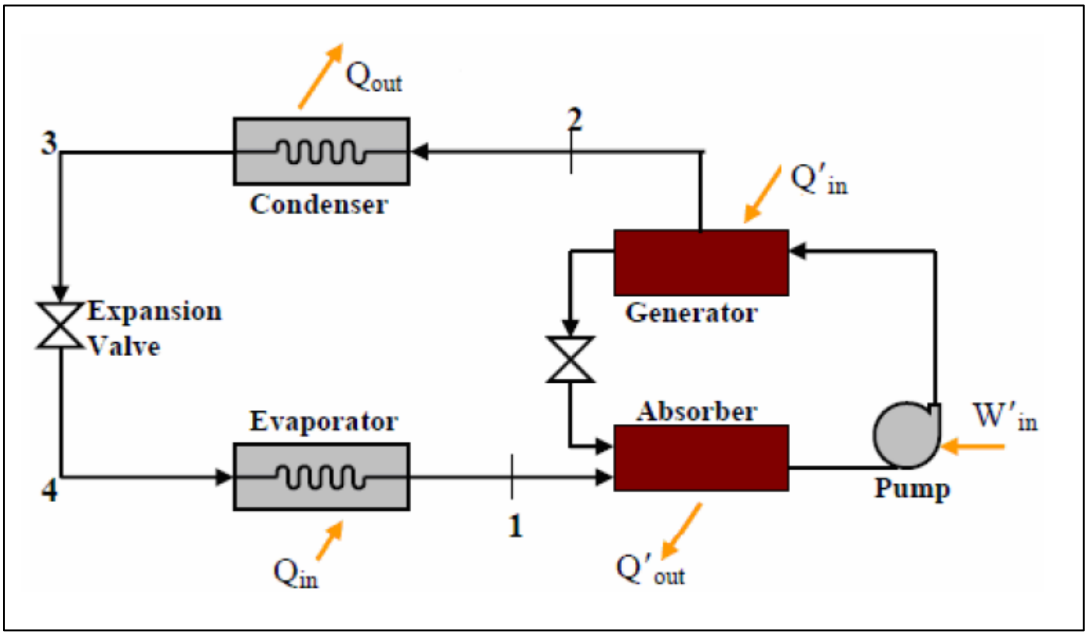


Figure 2.3: Schematic diagram of vapour absorption chiller

Source: Absorption Chillers Guideline by New Buildings Institute, 1998

When considering the process of the system, refrigerant enter to the evaporator as a cool and low pressure liquid and vapour mixture (reference point of the diagram is 4). Then heat is transferred from warm water to the refrigerant and it will influenced to the boiling of liquid refrigerant. By considering an analogy of the vapour compression system, the absorber in absorption system perform as suction side of the compressor, which draws the refrigerant vapour (reference point of the diagram is 1) to mix with absorbent. The pump perform compression process and it is used to drives the mixture of both absorbent and refrigerant to the high pressure side. The generator perform as a discharge of the compressor, which delivers the refrigerant vapour (reference point of the diagram is 2) to the system.

Then refrigerant vapour (reference point of the diagram is 2) depart from the generator will enter to the condenser and heat is transferred to water at lower temperature by condensing refrigerant vapour in to liquid. Subsequently, this liquid refrigerant (reference point of the diagram is 3) will flows to the expansion valve and it creates required pressure drop for the evaporator. Then again create the mixture of both liquid and vapour refrigerant (reference point of the diagram is 4) and it will travel to the evaporator in order to recurrence the cycle.

2.3.5 Types of absorption chillers

Absorption chillers can be mainly classified as direct-fired, indirect-fired based on heat source as well as single, double and triple effect based on technology. By considering direct-fired chillers, gas or other fuel that can be burned in the unit are used as a heat source. Indirect-fired units are used steam or some other fluid that can be transferred heat from another source, such as waste heat recovered from an industrial process or a boiler. In addition to that, hybrid systems are relatively common in absorption chillers which are able to combine with gas and electric systems in order to both load optimization and operation flexibility.

Single effect chillers

The single effect vapour absorption cycle consist of fluid transfer process through major components of the system such as, evaporator, absorber, generator and condenser, which is illustrated in the pressure and temperature diagram in Figure 2.4.

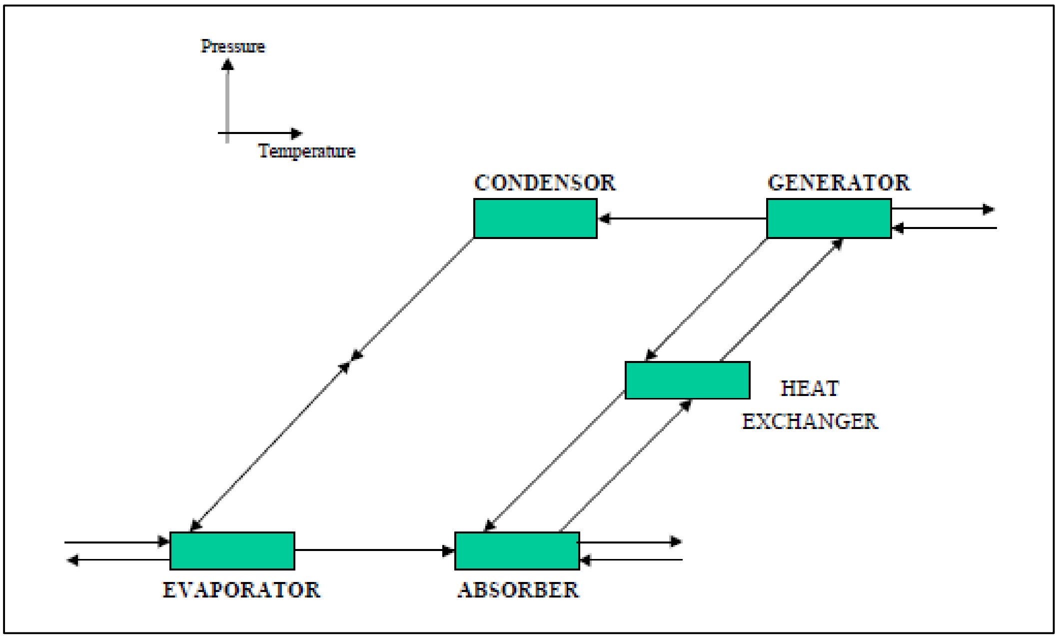


Figure 2.4: Schematic of single effect vapour absorption chiller

Source: Absorption Chillers Guideline by New Buildings Institute, 1998

Single-effect LiBr/H_2O absorption chillers are used either low pressure steam or hot water as a heat source. During this process, water will evaporate and consequently extract heat through evaporator, because of the system is at a partial vacuum condition. But, thermal efficiency of single effect absorption chillers are low compared to other systems. State of the art single effect chillers are used in applications, such as waste heat is freely available. In addition to that, single effect systems can be used for the purpose of chilled water productions, such as air conditioning and process water cooling. Also single effect systems are available in wide range of capacities from 7.5 to 1,500 tons.

Double effect chillers

Double-effect LiBr/H_2O absorption chillers have designed to achieve higher efficiency with the development. Main difference of double effect chiller from the single effect machine can be identified as there are two generators and two condensers in order to provide more refrigerant to boil off from the fluid mixture. Figure 2.5 shows schematic diagram of the double effect absorption cycle based on pressure and temperature. During this process, high temperature generator consumed externally provided steam in order to boil the refrigerant with weak absorbent. Consequently, refrigerant vapour generated in high temperature generator is condensed and heat produced is used to heat the low temperature generator.

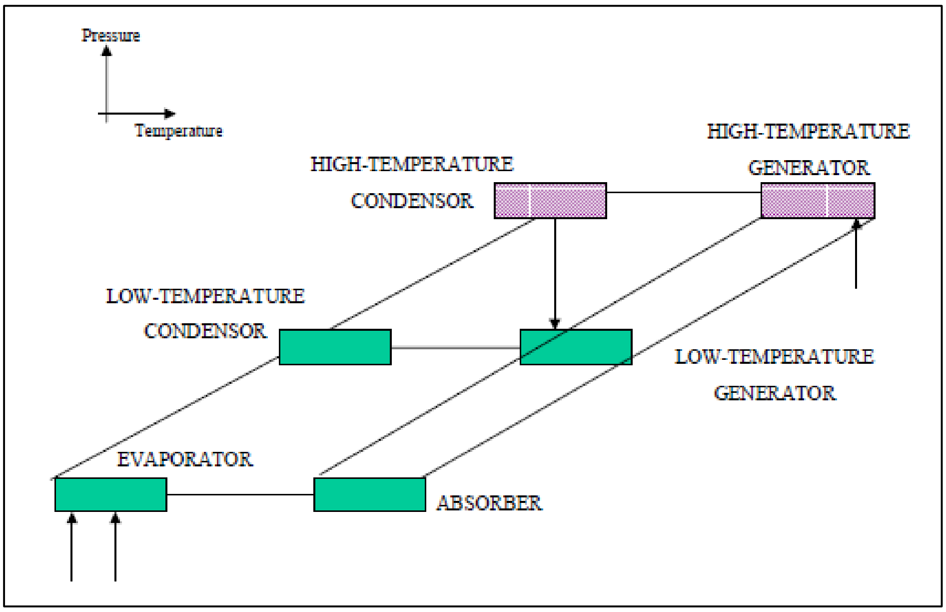


Figure 2.5: Schematic of double effect vapour absorption chiller

Source: Absorption Chillers Guideline by New Buildings Institute, 1998

These double effect machines usually use high pressure steam or gas fired combustors as a heat source. Double effect chillers can be used for air conditioning systems and process cooling systems in some places, especially cost of electricity is significantly higher than natural gas. Double effect machines are also used in places such as, high pressure steam, district heating steam, is freely available. Even though the double effect machines are more efficient than single-effect machines, they have higher initial manufacturing cost. There are special materials considerations, because of increased corrosion rates (higher operating temperatures than single effect machines), larger heat exchanger surface areas, and more complicated control systems.

Triple effect chillers

Triple effect vapour absorption chillers are the improved system over the double effect system. Figure 2.6 shows schematic diagram of the triple effect absorption cycle based on a pressure and temperature. During this process, refrigerant vapour from both high and medium temperature generators will be condensed and discharged heat is used to heat low temperature generator. Then refrigerant fluid from all three condensers will flows to an evaporator, which can be able to absorb more heat.

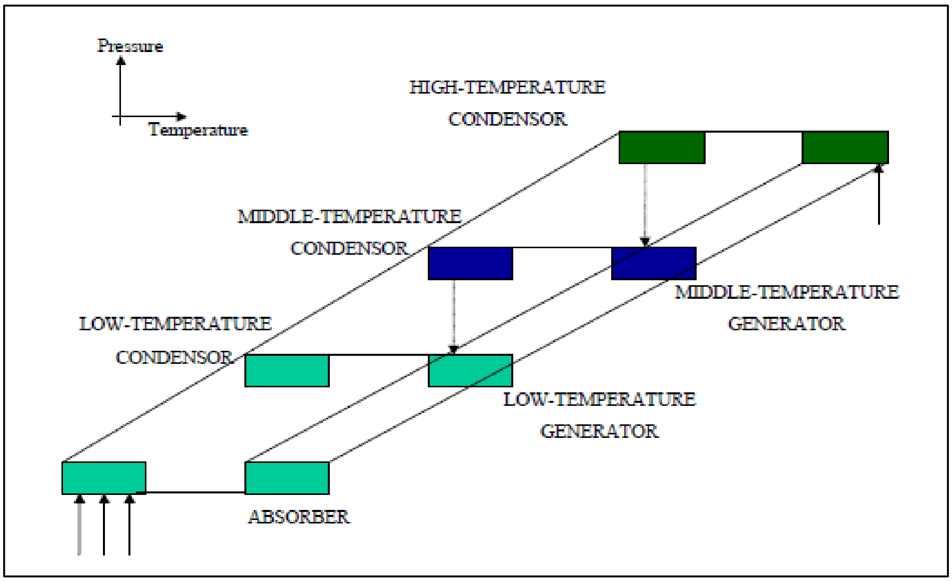


Figure 2.6: Schematic of triple effect vapour absorption chiller

Source: Absorption Chillers Guideline by New Buildings Institute, 1998

Two different triple effect vapour absorption chiller cycles are accomplished of significant performance enhancements over corresponding double effect chillers. One chiller uses two condensers and two absorbers to accomplish the triple effect. Second chiller uses double condenser coupled (DCC) triple effect, which uses three condensers and a sub-cooler for third condenser. Triple effect chillers can be provide higher thermal efficiencies, where equal to electrical chillers. However, cost will be higher and therefore system financial feasibility need to be assessed.

2.4 Research gaps

Waste heat recovery from exhaust flue gases is usually practiced in many instances rather than other areas having significant potential to recover waste heat, especially from the boiler blow down water in large coal fired power stations.

Mathematical model for the energy extracted per unit capital cost for the waste heat recovery from boiler blow down water system of coal fired power station has not yet derived.

3 METHODOLOGY

3.1 Potential waste heat availability from boiler blowdown system

Due to similarity of all three boilers and auxiliaries in all ways, data was collected based on LVPS unit 02 boiler. Coal fired power plants are categorized as based load generation systems and therefore data was taken at 300 MW which is the rated maximum continuous operating load.

To find the waste heat availability of boiler blowdown water in boiler, it was required to collect operating data of boiler steam drum and CBD flash tank. Collected data are summarized in Table 3.1 as follows,

Table 3.1: Operating data of boiler steam drum and CBD flash tank

Parameter at 300 MW	**Boiler steam drum**	**CBD flash tank**
Operating pressure (P)	17 MPa	1.4 MPa
Saturation temperature (T)	353 ^{0}C	198 ^{0}C
Blowdown flow rate ($\dot{M}$)	10,250 kg/h	-

CBD flash tank recovered generated flash steam in to deareator through steam piping and remaining balance of saturated water was having significant amount of energy as waste heat. To calculate amount of waste heat availability, it was required to find out rate of flash steam generation (equation 3.1) and then can be calculated mass flow rate of waste heat according to equation 3.2 for one unit.

$$\text{fraction of flash steam generated} = \frac{(h_{f1} - h_{f2})}{h_{fq2}} \tag{3.1}$$

Where,

h_{f1}: Liquid enthalpy of water at boiler steam drum in kJ/kg

h_{f2}: Liquid enthalpy of water at CBD flash tank in kJ/kg

h_{fq2}: Enthalpy of evaporation at CBD flash tank in kJ/kg

$$\dot{m} = \dot{M} \times \left\{1 - \left\{\frac{(h_{f1} - h_{f2})}{h_{fq2}}\right\}\right\} \frac{kg}{h} \qquad (3.2)$$

Where,

$\dot{m}$: Waste heat mass flow rate in one boiler in kg/h

$\dot{M}$: Boiler continuous blowdown rate in kg/h

By considering all three boilers, total available waste heat flow and enthalpy can be calculated using 3.3, 3.4 and 3.5 equations respectively.

$$\text{total available waste heat flow rate} = 3\dot{m} \ \frac{kg}{h} \qquad (3.3)$$

$$\begin{aligned}&\text{available enthalpy of one boiler waste heat}\\ &= \dot{m} \times h_{f2} \times \frac{1}{3600} \ kW\end{aligned} \qquad (3.4)$$

$$\begin{aligned}&\text{total available enthalpy from three boilers}\\ &= 3\dot{m} \times h_{f2} \times \frac{1}{3600} \ kW\end{aligned} \qquad (3.5)$$

3.2 Energy recovery opportunities in Lakvijaya power station from boiler blowdown

Lakvijaya coal power station totally studied to find the opportunities to recover total available enthalpy (equation 3.5) to useful manner and identified opportunities in condensate water pre heating system and air conditioning systems.

3.2.1 Waste heat recovery LP heater for condensate water preheating

Extracted part of unit 02 power plant total energy balance drawing is showing in Figure 3.1 which is basically focused on condensate water system of the plant and it was useful to identify location for waste heat recovery new LP heater for the system.

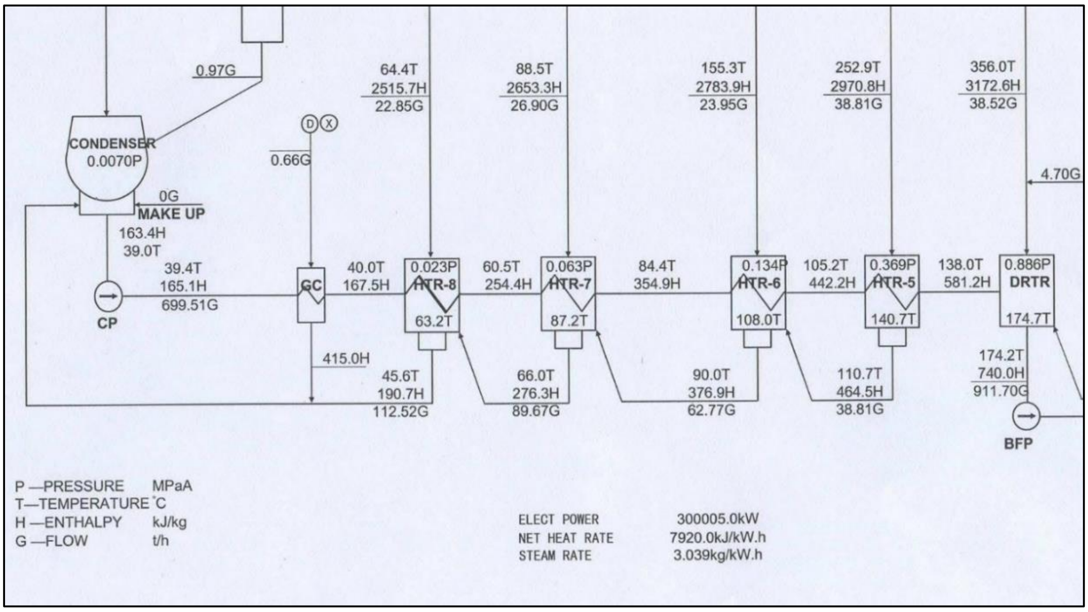


Figure 3.1: Energy balance data of condensate water system

Source: Heat and Mass Balance of LVPS unit 02

3.2.2 Vapour absorption chiller for air conditioning system

Checked the possibility to run the vapour absorption chiller to either fully or partially replace electrically driven vapour compression chillers for air conditioning systems in power plant premises. Details of the vapour compression chillers of the power station can be identified in Table 3.2.

Table 3.2: Details of the vapour compression chillers of the power station

Details of centralized air conditioning systems	**Users**
Main power block – Unit 01 power plant	Central control room, electronic cabinet rooms (unit 01 and 02), ESP and ash handling control room (Unit 01)
Main power block – Unit 03 power plant	electronic cabinet rooms (Unit 03), ESP and ash handling control room (Unit 02 and 03), Engineers room (Unit 03)
Boiler make-up water plant block	Boiler makeup water plant control room, laboratory rooms, canteen, administration building

Checked the possibility for opportunities of these two system separately and combining for waste heat extraction and therefore, introduced layout to analyse energy extraction at different conditions. Existing layout of boiler blowdown system shown in Figure 3.2 and proposed system layout with existing devices and new components are shown in Figure 3.3. Energy, cost and optimum sizes of each component will be calculated in next sections.

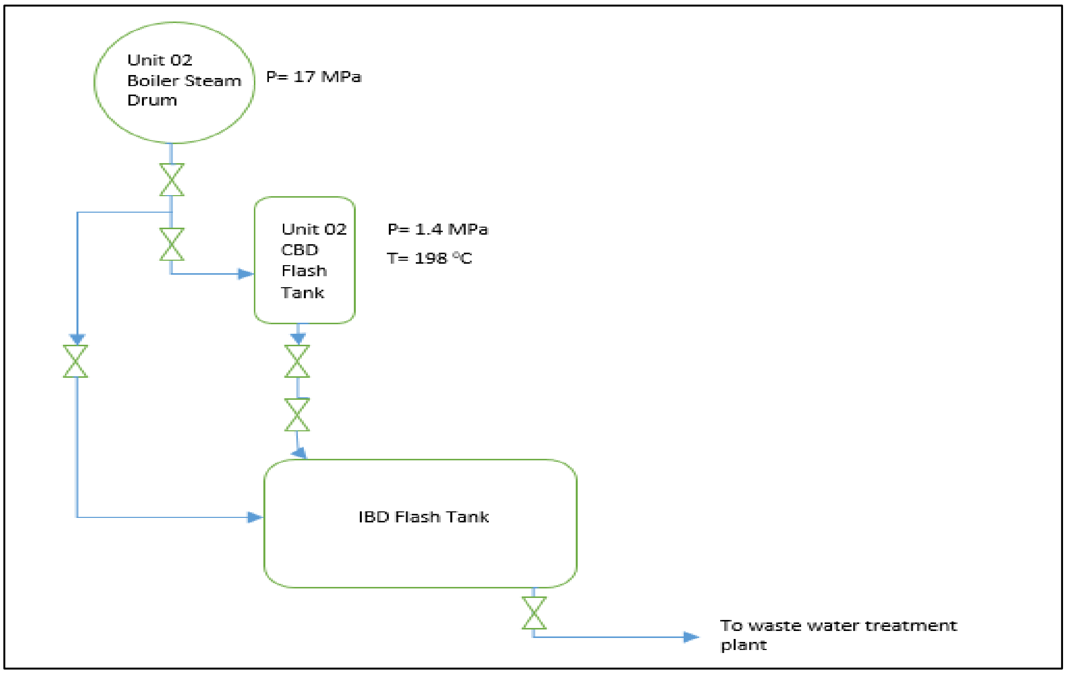


Figure 3.2: Existing layout of boiler blowdown system

Source: P & ID of boiler blowdown system of LVPS unit 02

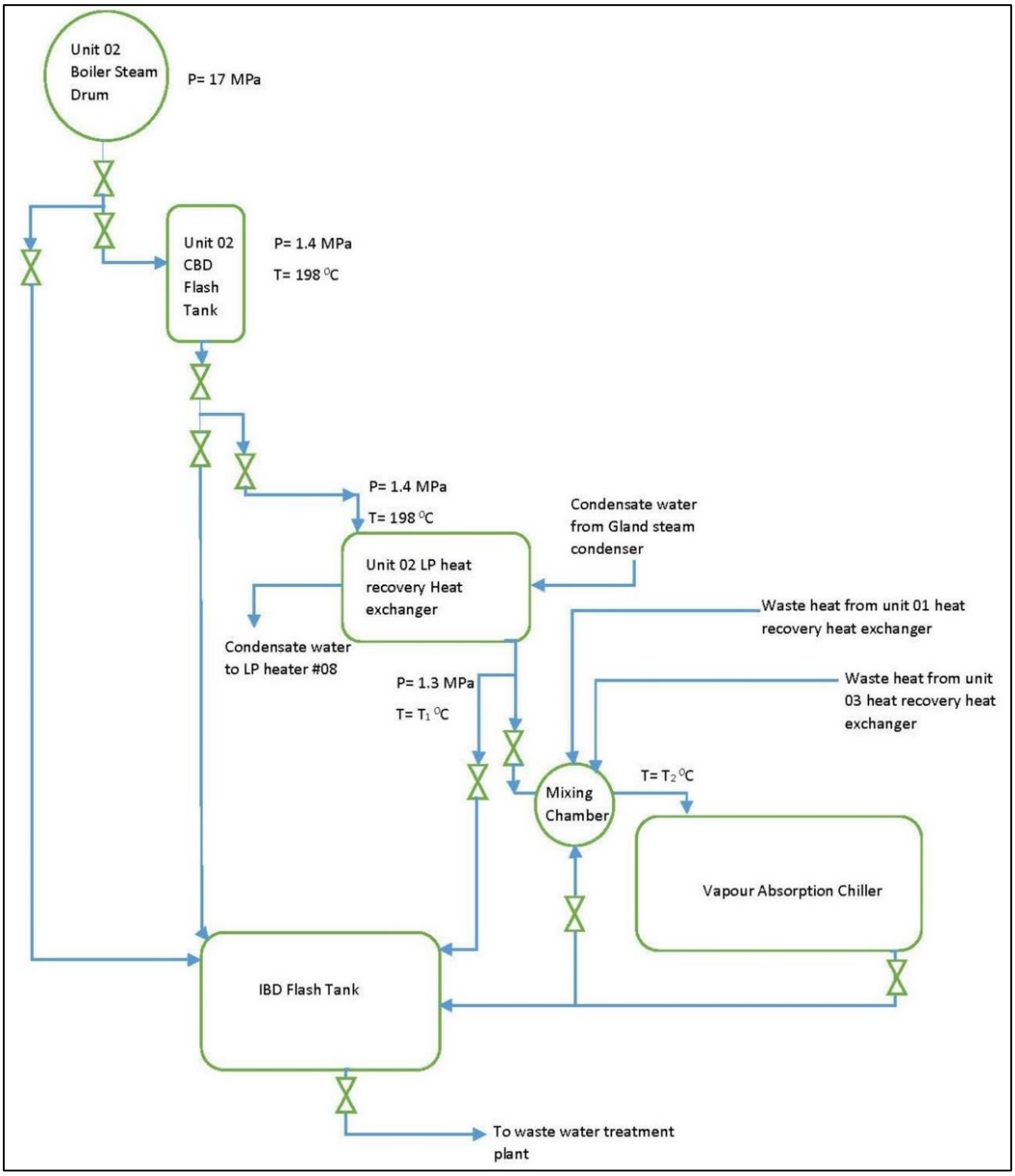


Figure 3.3: Proposed system layout of boiler blowdown

Source: P & ID of boiler blowdown and condensate water systems of LVPS

Brief description of newly added parts and components which are required to all three units are listed as follows in Table 3.3.

Table 3.3: Brief description of newly added parts and components

Component	Qty.	Description
LP heat exchanger	03	One heat exchanger required for one unit. Assumed to operate without phase changes in waste heat side water.
Vapour absorption chiller	01	Common for all three units. Assumed to operate without phase changes in hot water side and therefore, only single effect absorption chillers are considered.
Mixing chamber	01	Direct type and single phase fluids
Pipe and fittings	bulk	Should be select according to the design

3.3 Gathering data from identified systems in order to analyse

Historical operating data of gland steam condenser and LP heater no 08 has been collected and summarized in Table 3.4. These values of parameters has taken for energy calculations and analysis in next sections.

Table 3.4: Historical operating data of gland steam condenser and LP heater no 08

Parameters in condensate side	gland steam condenser	LP heater no 08
Inlet temperature (^{0}C)	39.4	40.0
Outlet temperature (^{0}C)	40.0	60.5
Operating pressure (MPa)	3.5	3.5
Mass flow rate ($\dot{M}_c$) (kg/h)	699,510	699,510

In addition to the condensate system data, following data are used to cost analysis which are based on CAPCOST ver2 computer based programme. Heat exchanger data and material data are shown in Table 3.5 and Table 3.6 respectively.

Table 3.5: Heat exchanger data based on CAPCOST ver2

Heat Exchanger Data	**Parameters**										
Exchanger Type	K_1	K_2	K_3	C_1	C_2	C_3	B_1	B_2	A_{min} (m2)	A_{max} (m2)	P_{max} (barg)
Double Pipe	3.34	0.27	-0.047	13.14	-12.65	3.07	1.74	1.55	1	10	300
40 barg < P < 100 barg	0			0.60	-0.91	0.3					
P < 40 barg				0	0	0					
Multiple Pipe	2.76	0.72	0.078	13.14	-12.65	3.07	1.74	1.55	10	100	300
40 barg < P < 100 barg				0.60	-0.91	0.33					
P < 40 barg				0	0	0					
Fixed tube, sheet, or U tube	4.32	-0.30	0.163	0.038	-0.11	0.081	1.63	1.66	10.0	1000	140
tubes only > 5 barg				-0.001	-0.006	0.01					
Floating Head	4.83	-0.85	0.318	0.038	-0.11	0.081	1.63	1.66	10.0	1000	140
tubes only > 5barg				-0.001	-0.006	0.01					
Bayonet	4.27	-0.04	0.143	0.038	-0.11	0.081	1.63	1.66	10.0	1000	140
tubes only > 5 barg				-0.001	-0.006	0.01					
Kettle Reboiler	4.46	-0.52	0.395	0.038	-0.11	0.081	1.63	1.66	10.0	100	140
tubes only > 5 barg				-0.001	-0.006	0.01					
Scraped Wall	3.78	0.85	0.034	13.14	-12.65	3.07	1.74	1.55	2.0	20	300
40 barg < P < 100 barg				0.60	-0.91	0.33					
P < 40 barg				0	0	0					
Teflon Tube	3.80	0.89	-0.167	0	0	0	1.63	1.66	1.0	10	15
Air Cooler	4.03	0.23	0.049	-0.12	0.15	-0.028	0.96	1.21	10	10000	100
Spiral Tube - shell and tube	3.99	0.06	0.243	-0.40	0.18	0	1.74	1.55	1	100	400
tube only				-0.21	0.097	0					
Spiral Plate	4.65	-0.29	0.220	0	0	0	0.96	1.21	1	100	19
Flat Plate	4.66	-0.15	0.154	0	0	0	0.96	1.21	10	1000	19

Table 3.6 Materials data based on CAPCOST ver2

Material Factors (F_M)	**Parameters**								
	Shell - CS	CS	Cu	CS	SS	CS	Ni	CS	Ti
Exchanger Type	Tube - CS	Cu	Cu	SS	SS	Ni	Ni	Ti	Ti
Double Pipe	1.00	1.35	1.69	1.81	2.73	2.68	3.73	4.63	11.38
Multiple Pipe	1.00	1.35	1.69	1.81	2.73	2.68	3.73	4.63	11.38
Fixed tube, sheet, or U tube	1.00	1.35	1.69	1.81	2.73	2.68	3.73	4.63	11.38
Floating Head	1.00	1.35	1.69	1.81	2.73	2.68	3.73	4.63	11.38
Bayonet	1.00	1.35	1.69	1.81	2.73	2.68	3.73	4.63	11.38
Kettle Reboiler	1.00	1.35	1.69	1.81	2.73	2.68	3.73	4.63	11.38
Scraped Wall	1.00	1.35	1.69	1.81	2.73	2.68	3.73	4.63	11.38
Spiral Tube	1.00	1.35	1.69	1.81	2.73	2.68	3.73	4.63	11.38

Chiller plant name plate data has collected to find capacity and availability of cooling load by vapour absorption chiller. Cooling capacity data has summarized in Table 3.7.

Table 3.7: Cooling capacity of existing chillers

Details of centralized air conditioning systems	**Cooling capacity of chillers (kW)**
Main Power Block – Unit 01 Power Plant	900
Main Power Block – Unit 03 Power Plant	960
Boiler Make-up Water Plant Block	640

Furthermore, checked the applicability of both single stage and two stage vapour absorption chillers for these kind of systems and therefore, it was required cooling capacity data of single stage and double stage vapour absorption chillers with different hot water mas flow rate. Therefore, referred catalogues which are supplied by same manufacturer named as SHUANGLIANG and collected cooling capacity data of double stage and single stage chillers are summarized in Figure 3.4 and Figure 3.5 respectively.

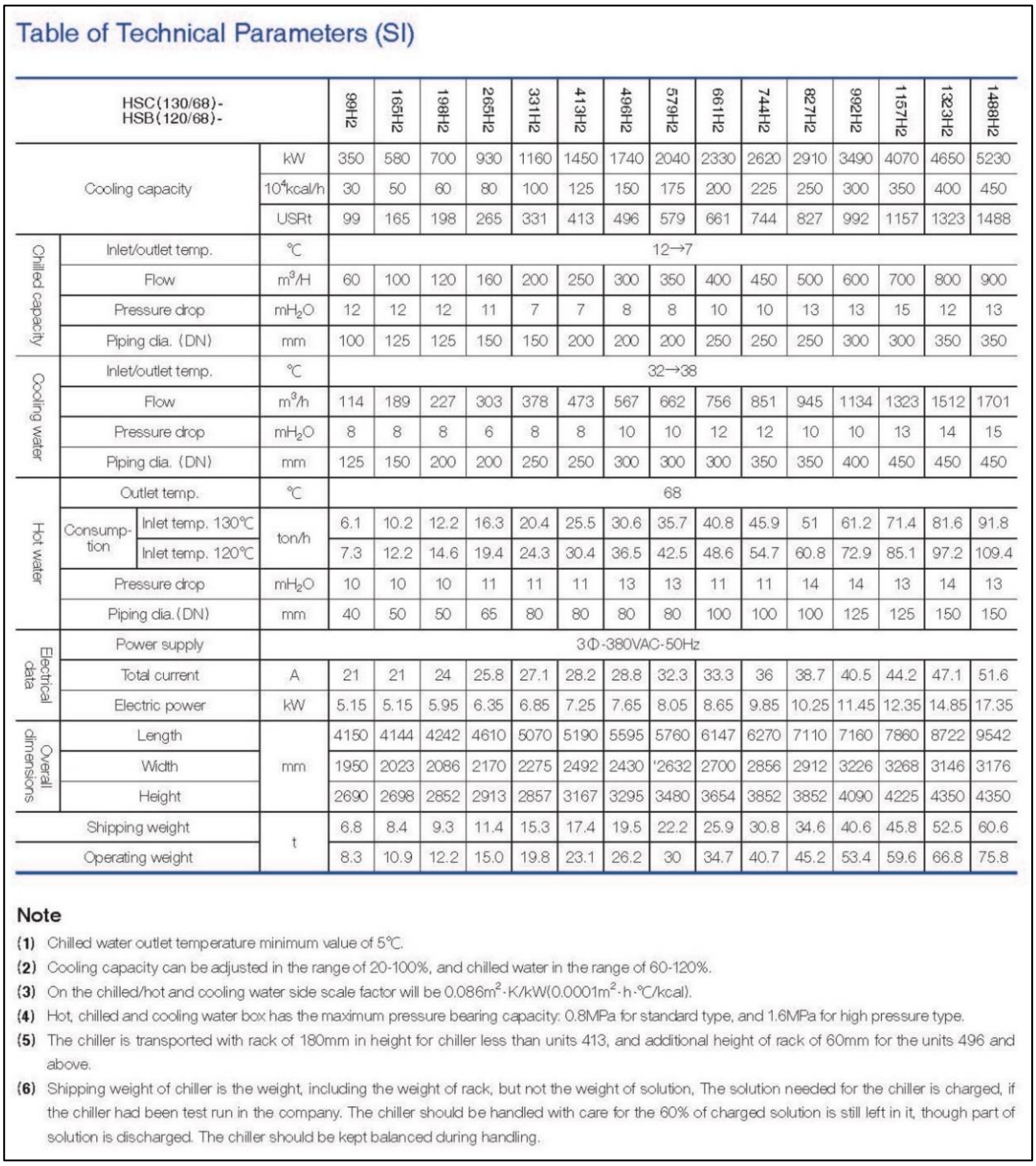


Table of Technical Parameters (SI)

HSC(130/68)- HSB(120/68)-				99H2	165H2	198H2	265H2	331H2	413H2	496H2	579H2	661H2	744H2	827H2	992H2	1157H2	1323H2	1488H2
Cooling capacity			kW	350	580	700	930	1160	1450	1740	2040	2330	2620	2910	3490	4070	4650	5230
			10^4kcal/h	30	50	60	80	100	125	150	175	200	225	250	300	350	400	450
			USRt	99	165	198	265	331	413	496	579	661	744	827	992	1157	1323	1488
Chilled capacity	Inlet/outlet temp.		℃	12→7														
	Flow		m^3/H	60	100	120	160	200	250	300	350	400	450	500	600	700	800	900
	Pressure drop		mH_2O	12	12	12	11	7	7	8	8	10	10	13	13	15	12	13
	Piping dia. (DN)		mm	100	125	125	150	150	200	200	200	250	250	250	300	300	350	350
Cooling water	Inlet/outlet temp.		℃	32→38														
	Flow		m^3/h	114	189	227	303	378	473	567	662	756	851	945	1134	1323	1512	1701
	Pressure drop		mH_2O	8	8	8	6	8	8	10	10	12	12	10	10	13	14	15
	Piping dia. (DN)		mm	125	150	200	200	250	250	300	300	300	350	350	400	450	450	450
Hot water	Outlet temp.		℃	68														
	Consumption	Inlet temp. 130℃	ton/h	6.1	10.2	12.2	16.3	20.4	25.5	30.6	35.7	40.8	45.9	51	61.2	71.4	81.6	91.8
		Inlet temp. 120℃		7.3	12.2	14.6	19.4	24.3	30.4	36.5	42.5	48.6	54.7	60.8	72.9	85.1	97.2	109.4
	Pressure drop		mH_2O	10	10	10	11	11	11	13	13	11	11	14	14	13	14	13
	Piping dia.(DN)		mm	40	50	50	65	80	80	80	80	100	100	100	125	125	150	150
Electrical data	Power supply			3Φ-380VAC-50Hz														
	Total current		A	21	21	24	25.8	27.1	28.2	28.8	32.3	33.3	36	38.7	40.5	44.2	47.1	51.6
	Electric power		kW	5.15	5.15	5.95	6.35	6.85	7.25	7.65	8.05	8.65	9.85	10.25	11.45	12.35	14.85	17.35
Overall dimensions	Length		mm	4150	4144	4242	4610	5070	5190	5595	5760	6147	6270	7110	7160	7860	8722	9542
	Width			1950	2023	2086	2170	2275	2492	2430	'2632	2700	2856	2912	3226	3268	3146	3176
	Height			2690	2698	2852	2913	2857	3167	3295	3480	3654	3852	3852	4090	4225	4350	4350
Shipping weight			t	6.8	8.4	9.3	11.4	15.3	17.4	19.5	22.2	25.9	30.8	34.6	40.6	45.8	52.5	60.6
Operating weight				8.3	10.9	12.2	15.0	19.8	23.1	26.2	30	34.7	40.7	45.2	53.4	59.6	66.8	75.8

Note

(1) Chilled water outlet temperature minimum value of 5℃.

(2) Cooling capacity can be adjusted in the range of 20-100%, and chilled water in the range of 60-120%.

(3) On the chilled/hot and cooling water side scale factor will be 0.086m^2·K/kW(0.0001m^2·h·℃/kcal).

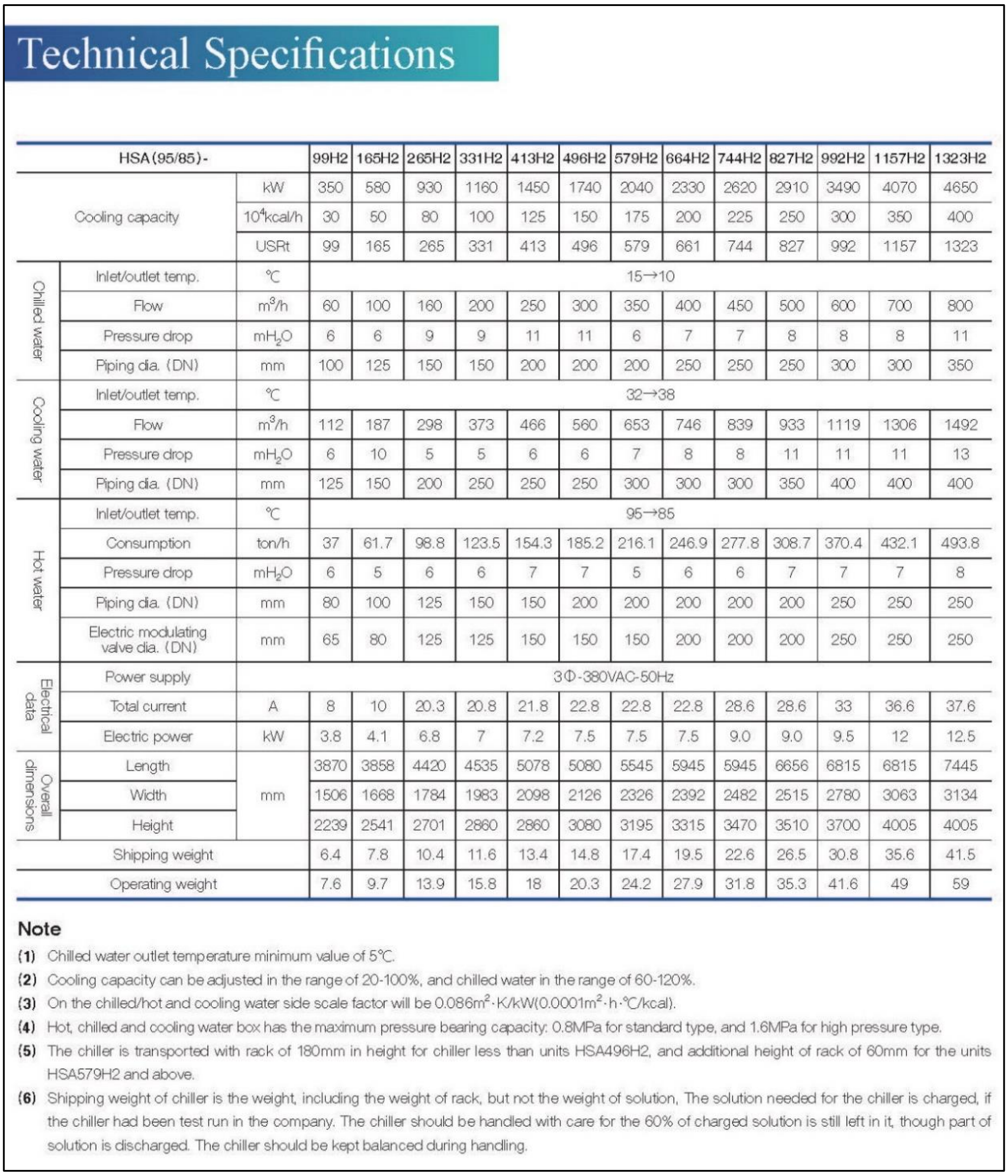
(4) Hot, chilled and cooling water box has the maximum pressure bearing capacity: 0.8MPa for standard type, and 1.6MPa for high pressure type.

(5) The chiller is transported with rack of 180mm in height for chiller less than units 413, and additional height of rack of 60mm for the units 496 and above.

(6) Shipping weight of chiller is the weight, including the weight of rack, but not the weight of solution, The solution needed for the chiller is charged, if the chiller had been test run in the company. The chiller should be handled with care for the 60% of charged solution is still left in it, though part of solution is discharged. The chiller should be kept balanced during handling.

Figure 3.4: Cooling capacity data of two stage absorption chiller

Source: SHUANGLIANG Absorption Chiller Product Catalogue by Jiangsu Shuangliang Air-Conditioning Equipment Co., Ltd,



Technical Specifications

HSA(95/85)-			99H2	165H2	265H2	331H2	413H2	496H2	579H2	664H2	744H2	827H2	992H2	1157H2	1323H2
Cooling capacity		kW	350	580	930	1160	1450	1740	2040	2330	2620	2910	3490	4070	4650
		10^4kcal/h	30	50	80	100	125	150	175	200	225	250	300	350	400
		USRt	99	165	265	331	413	496	579	661	744	827	992	1157	1323
Chilled water	Inlet/outlet temp.	℃	15→10												
	Flow	m^3/h	60	100	160	200	250	300	350	400	450	500	600	700	800
	Pressure drop	mH_2O	6	6	9	9	11	11	6	7	7	8	8	8	11
	Piping dia. (DN)	mm	100	125	150	150	200	200	200	250	250	250	300	300	350
Cooling water	Inlet/outlet temp.	℃	32→38												
	Flow	m^3/h	112	187	298	373	466	560	653	746	839	933	1119	1306	1492
	Pressure drop	mH_2O	6	10	5	5	6	6	7	8	8	11	11	11	13
	Piping dia. (DN)	mm	125	150	200	250	250	250	300	300	300	350	400	400	400
Hot water	Inlet/outlet temp.	℃	95→85												
	Consumption	ton/h	37	61.7	98.8	123.5	154.3	185.2	216.1	246.9	277.8	308.7	370.4	432.1	493.8
	Pressure drop	mH_2O	6	5	6	6	7	7	5	6	6	7	7	7	8
	Piping dia. (DN)	mm	80	100	125	150	150	200	200	200	200	200	250	250	250
	Electric modulating valve dia. (DN)	mm	65	80	125	125	150	150	150	200	200	200	250	250	250
Electrical data	Power supply		3Φ-380VAC-50Hz												
	Total current	A	8	10	20.3	20.8	21.8	22.8	22.8	22.8	28.6	28.6	33	36.6	37.6
	Electric power	kW	3.8	4.1	6.8	7	7.2	7.5	7.5	7.5	9.0	9.0	9.5	12	12.5
Overall dimensions	Length	mm	3870	3858	4420	4535	5078	5080	5545	5945	5945	6656	6815	6815	7445
	Width		1506	1668	1784	1983	2098	2126	2326	2392	2482	2515	2780	3063	3134
	Height		2239	2541	2701	2860	2860	3080	3195	3315	3470	3510	3700	4005	4005
Shipping weight			6.4	7.8	10.4	11.6	13.4	14.8	17.4	19.5	22.6	26.5	30.8	35.6	41.5
Operating weight			7.6	9.7	13.9	15.8	18	20.3	24.2	27.9	31.8	35.3	41.6	49	59

Note

(1) Chilled water outlet temperature minimum value of 5℃.

(2) Cooling capacity can be adjusted in the range of 20-100%, and chilled water in the range of 60-120%.

(3) On the chilled/hot and cooling water side scale factor will be $0.086m^2 \cdot K/kW(0.0001m^2 \cdot h \cdot ℃/kcal)$.

(4) Hot, chilled and cooling water box has the maximum pressure bearing capacity: 0.8MPa for standard type, and 1.6MPa for high pressure type.

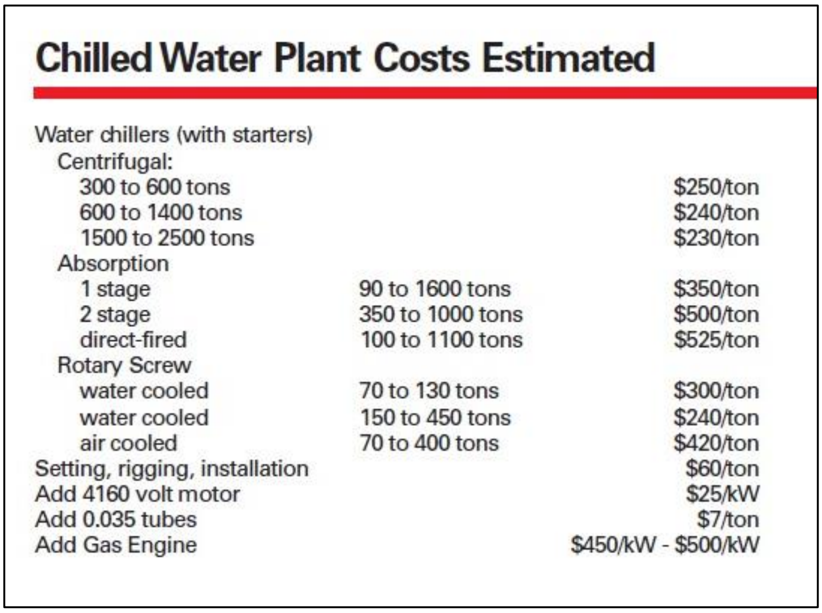
(5) The chiller is transported with rack of 180mm in height for chiller less than units HSA496H2, and additional height of rack of 60mm for the units HSA579H2 and above.

(6) Shipping weight of chiller is the weight, including the weight of rack, but not the weight of solution, The solution needed for the chiller is charged, if the chiller had been test run in the company. The chiller should be handled with care for the 60% of charged solution is still left in it, though part of solution is discharged. The chiller should be kept balanced during handling.

Figure 3.5: Cooling capacity data of single stage absorption chiller

Source: SHUANGLIANG Absorption Chiller Product Catalogue by Jiangsu Shuangliang Air-Conditioning Equipment Co., Ltd,

Vapour absorption chiller plant cost calculated with reference to typical cost values which are given by TRANE that is one of the chiller plant manufacturer in the world and related data are given in Figure 3.6.



Chilled Water Plant Costs Estimated

Water chillers (with starters)		
Centrifugal:		
300 to 600 tons		$250/ton
600 to 1400 tons		$240/ton
1500 to 2500 tons		$230/ton
Absorption		
1 stage	90 to 1600 tons	$350/ton
2 stage	350 to 1000 tons	$500/ton
direct-fired	100 to 1100 tons	$525/ton
Rotary Screw		
water cooled	70 to 130 tons	$300/ton
water cooled	150 to 450 tons	$240/ton
air cooled	70 to 400 tons	$420/ton
Setting, rigging, installation		$60/ton
Add 4160 volt motor		$25/kW
Add 0.035 tubes		$7/ton
Add Gas Engine		$450/kW - $500/kW

Figure 3.6: Typical capital cost estimated for chiller plants

Source: Quick Reference for Efficient Chiller System Design by TRANE, 2000

3.4 Data analysis in order to waste heat recovery

For the energy and cost analysis, there were two main independent variables considered within the system shown in Figure 3.7 and all relevant parameters were marked. Boiler continuous blowdown rate $(\dot{M})$ and LP heat recovery heat exchanger outlet temperature (T_1) were changed and observed variation in energy extraction from LP heaters, heat transfer area of LP heaters, heaters total grass root cost, cooling capacities of single stage and two stage absorption chillers, chillers cost, and combine systems total energy extraction, combine system total cost and total system energy extraction per unit cost. These analysis will be discussed separately under LP heater analysis, chillers analysis and combined systems analysis sections.

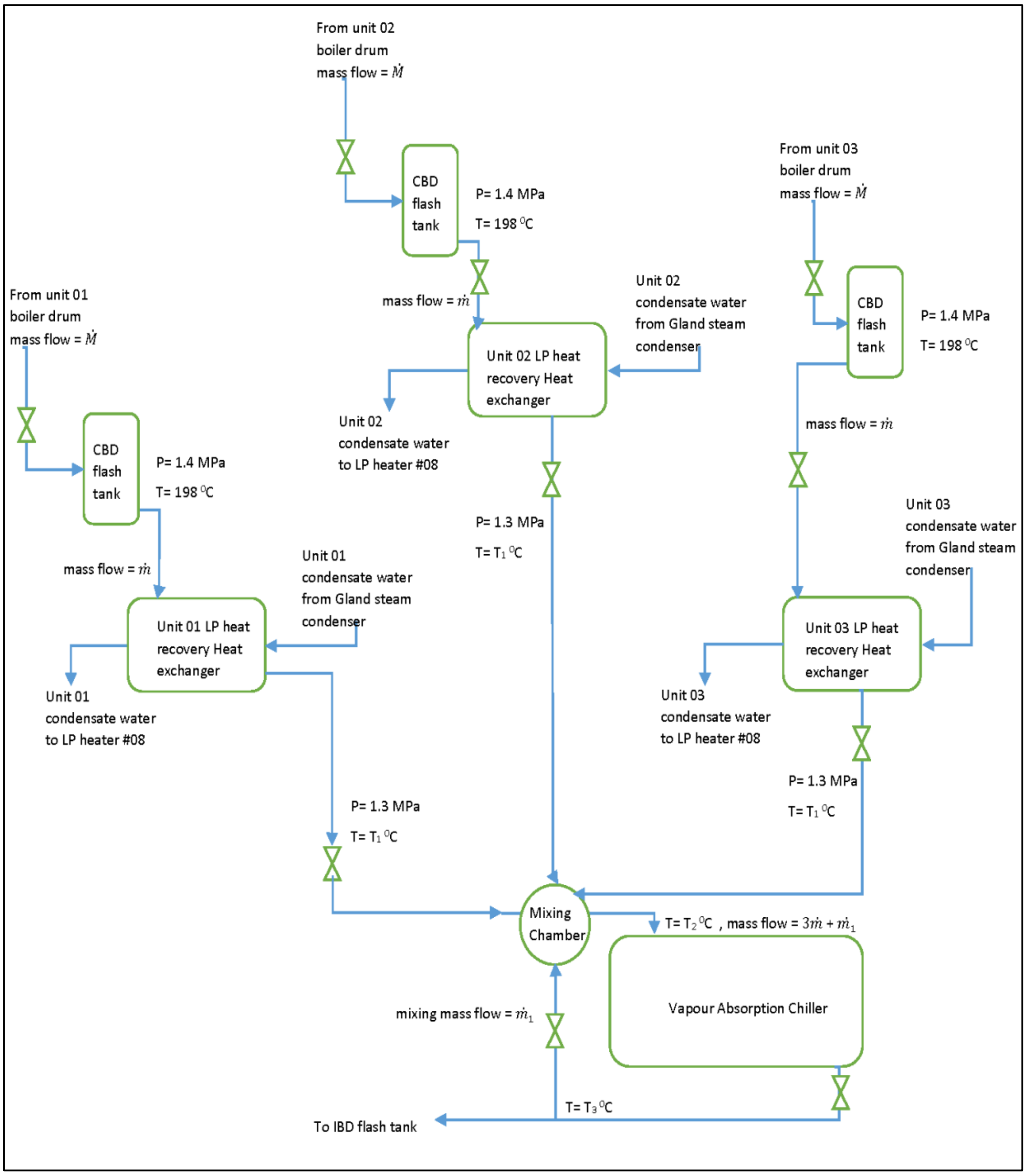


Figure 3.7: Descriptive layout with new components

Source: P & ID of boiler blowdown and condensate water systems of LVPS

3.4.1 LP heaters analysis

Energy extracted by LP heater has calculated by changing LP heater outlet waste heat fluid temperature (T_1) from 190 ^{0}C to 45 ^{0}C by 5 ^{0}C intervals keeping boiler blowdown flow rate ($\dot{M}$) at constant for one series of temperature variation. Then repeated energy calculation for different boiler blowdown rates ($\dot{M}$) from 1% BMCR to 3% BMCR by 0.5% BMCR intervals. Energy extracted by one heat exchanger(Q_1) and total energy extracted by all three heat exchangers(Q_h) were described by equation 3.6 and equation 3.7 respectively.

$$Q_1 = \dot{m} \times (h_{hi} - h_{ho}) \times \frac{1}{3600}\ kW \quad (3.6)$$

$$Q_h = 3\dot{m} \times (h_{hi} - h_{ho}) \times \frac{1}{3600}\ kW \quad (3.7)$$

Where,

Q_1 : Energy extracted by one heat exchanger in kW

Q_h : Energy extracted by all three heat exchangers in kW

h_{hi}: Specific enthalpy of waste heat fluid inlet to the heat exchanger in kJ/kg

h_{ho}: Specific enthalpy of waste heat fluid outlet from the heat exchanger in kJ/kg

Extracted energy from LP heaters were influenced to temperature increment of condensate water and which will be described in equation 3.8.

$$T_{o\,hx} = T_{i\,hx} + \left(\frac{Q_1}{\dot{M}_c \times C_{P\,c}}\right) \times 3600\ ℃ \quad (3.8)$$

Where,

$T_{o\,hx}$: LP heater outlet condensate water temperature in ℃

$T_{i\,hx}$: LP heater inlet condensate water temperature in ℃

$\dot{M}_c$: Condensate water mass flow rate in kg/h

$C_{P\,c}$: Specific heat capacity at constant pressure of condensate water of LP heater inlet in kJ/kg ℃

Next step was calculation of heat exchanger capital cost for each scenario and used CAPCOST ver2 software was required inputs such as type of the heat exchanger, heat transfer surface area of heat exchanger, material selection of both shell and tube sides and maximum operating pressure of heat exchanger and those entered data were summarized in Table 3.8.

Table 3.8: Data used as inputs for CAPCOST ver2 software

Required data	specification	remarks
Type	Multiple tube	Tube side mas flow rate was very high.
Heat transfer area	10 – 100 m^2	CAPCOST ver2 programme has been limited. Linear regression was done to find heat exchanger cost more than 100 m2 of heat transfer area.
material	Carbon steel – carbon steel	Working fluid was demineralized water in both shell and tube sides. Therefore, these were the most economical materials.
Maximum operating pressure	3.5 MPa	Shell and tube thickness were depended on the maximum operating pressure.

Heat transfer area of LP heater has been calculated by using LMTD method of heat exchangers and which is given by the equation 3.9.

$$A = \left(\frac{Q_1}{U \times LMTD}\right) m^2 \qquad (3.9)$$

Where,

A : Heat transfer area in m^2

Q_1 : Energy extracted by one heat exchanger in kW

U: Overall heat transfer coefficient of heat exchanger in kW/m^2 ℃

$LMTD$: Log mean temperature difference of heat exchanger

$$LMTD = \frac{(T_0 - T_{o\,hx}) - (T_1 - T_{i\,hx})}{\ln(T_0 - T_{o\,hx}) - (T_1 - T_{i\,hx})} \qquad (3.10)$$

Where,

T_0 : Waste heat fluid inlet temperature to LP heater in ℃

T_1 : Waste heat fluid outlet temperature from LP heater in ℃

$T_{o\,hx}$: LP heater outlet condensate water temperature in ℃

$T_{i\,hx}$: LP heater inlet condensate water temperature in ℃

Heat transfer surface area of LP heater was calculated by taking overall heat transfer coefficient (U) as 0.25 kW/m^2 ^{0}C using above mentioned equations and variables. Calculated heat transfer area of LP heaters were varied form 0.9 m^2 to 281 m^2 by considering all variations. Due to limitation in CAPCOST ver2 programme, mathematical cost model was developed for heat exchanger capital cost using linear regression method by MINITAB computer based statistical analysis software as follows.

Data set preliminary analysis was done by using Scatter plot by Minitab software, Outlier test and Anderson Darling test for normality test which are imported to decide the type of statistical model, do the correction of data set if any outlier exist and that will lead to misinterpretation of data and since number of observations not large enough it must ensure the data are normally distributed respectively. After confirming the results, type of model has been decided and using statistical software, model was fitted and check the validity of model using ANOVA & R-square value.

Following steps were followed when analyse the data.

- Scatterplot was obtained for the dependent variable and independent variable to get the visualization trend of the data set. Using plotted points of Scatter plot graph it was observed the behaviour of the independent variable with dependent variable. And this scatter plot trend was useful to select the linear regression type which is most appropriate to fit. (That means regression model is linear or quadratic model)

- Checked the outliers of the data set to ensure that there were no data which misleading the analysis. For that purpose, Grubbs' test for outlier test has been used, since linear regression was sensitive to outliers. By using Grubbs' test, should be checked the hypothesis as below,

Hypothesis were as follows for the outlier test

Null hypothesis (H0) - There is no outliers in the data set
Alternative hypothesis (H1) - There are outliers in the data set
Significance level $\alpha = 0.05$

By using equation 3.11, Grubbs' test statistics was calculated by Statistical software Minitab and it was compared with considered significance level 0.05 and then checked that null hypothesis rejected or not. That means in considered data there exist the outliers or not.

The Grubbs' test statistics was defined in equation 3.11 as follows,

$$G = \frac{max|Y_i - \bar{Y}|}{s} \tag{3.11}$$

Where,

G : Grubbs' test statistics
Y_i : Observations which is belongs to the sample
$\bar{Y}$: Sample mean
s : Standard deviation of sample

The Grubbs' test statistic was the largest absolute deviation from the sample mean in units of the sample standard deviation.

Anderson darling test

Checked the normality test of variables using Anderson Darling test since linear regression analysis requires all variables to be multivariate normal. In here Test statistics obtained by using statistical software and it was compared with the significance level or p-value which also obtained by software and decided that data was normally distributed or not.

Anderson Darling Test statistics is defined as equation 3.12

$$A = n - \frac{1}{n}\sum_{i=1}^{n} \lfloor (2i-1)lnU_i + (2n+1-2i)ln(1-U_i) \rfloor \tag{3.12}$$

Where,

U_i : Theoretical (Gaussian) cumulative distribution at each point (X_i)

i: i^{th} observation and

n: Sample size

- Polynomial Regression model was fitted for the dependent variable and Independent variable to predict or estimate the grass root cost when varying the heat transfer area of LP heaters.

The k^{th} order polynomial model in one variable is given by,

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \cdots + \beta_k x^k + \varepsilon \qquad (3.13)$$

If $X_j = X^j$, j = 1,2,..k, then the model is multiple linear regressions model in k explanatory variables $X_1, X_2, \ldots, X_k$.. So the linear regression model $Y = X\beta + \varepsilon$ includes the polynomial regression model. Thus the techniques for fitting linear regression model can be used for fitting the polynomial regression model.

There are main assumptions done during fitted the regression model that is residuals are independent and normally distributed with mean zero. This assumption was checked using residual plots which was obtained by statistical software.

Analysis of Variance (ANOVA)

Using ANOVA Table, the appropriateness of model was checked. It was obtained by regression model was used to compares the fits of different linear models, the F test was used to assess multiple coefficients simultaneously. The F-test of the overall significance was a specific form of the F-test. It was compared a model with no predictors to the model that specify.

The hypotheses for the F-test of the overall significance are as follows:

Null hypothesis: The fit of the intercept-only model and fitted model are equal.

Alternative hypothesis: The fit of the intercept-only model is significantly reduced compared to fitted model

F test = variation between sample means / variation within the samples

3.4.2 Vapour absorption chillers analysis

Maximum available cooling capacities from single stage and two stage vapour absorption chillers were calculated for all variation of parameters simultaneously with LP heat exchanger calculations. LP heat exchanger outlet waste heat fluid temperature (T_1) and boiler blowdown rate ($\dot{M}$) were main independent variables for the analysis. Absorption chiller capacity was directly depend on the hot water mass flow rate at rated conditions. Therefore, mixing chamber was used to reduce hot water temperature, if it is higher the rated value. Vapour absorption chiller was not possible, if inlet hot water temperature is lower than the rated value and therefore cooling capacity was selected as zero in similar cases. Potential available hot water mass flow rate at rated conditions are described in equation 3.15 with respect to the mass balance of mixing chamber and equation 3.16 used to represent energy balance in mixing chamber respectively.

$$\dot{M}_{c\,i} = 3\dot{m} + \dot{m}_1 \; kg/h \tag{3.15}$$

Where,

$\dot{M}_{c\,i}$: Total hot water mass flow rate inlet to vapour absorption chiller in kg/h

$\dot{m}$: Waste heat fluid mass flow rate in kg/h

$\dot{m}_1$: Mixing water mass flow rate from outlet of chiller in kg/h

$$\dot{m}_1 = \frac{3\,\dot{m}C_{p1}(T_1 - T_2)}{C_{p2}(T_2 - T_3)} \; kg/h \tag{3.16}$$

Where,

$\dot{m}_1$: Mixing water mass flow rate from outlet of chiller in kg/h

$\dot{m}$: Waste heat fluid mass flow rate in kg/h

C_{p1} : Average specific heat capacity of waste heat fluid in kJ/kg ℃

C_{p2}: Average specific heat capacity of mixing fluid in kJ/kg ℃

T_1 : LP heat exchanger outlet waste heat fluid temperature in ℃

T_2 : Vapour absorption chiller hot water inlet temperature in ℃

T_3 : Vapour absorption chiller hot water outlet temperature in ℃

Calculated total hot water mass flow rate inlet ($\dot{M}_{c\,i}$) values at rated inlet temperature (T_2) was used to select compatible absorption chiller and chiller capacity from the catalogue (Table 3.8 and Table 3.9) for all variations of parameters.

Then typical cost calculated for each and every vapour absorption chiller by taking typical standard cost from Figure 3.4 and added 30% contingencies to find total capital cost. It was observed that some cooling capacities of two stage absorption chillers were out of range from the standard cost document (Figure 3.4). Hence added 10% more for typical unit price for those chillers. Total capital cost of two stage chillers from 350 tons – 1000 tons of cooling capacity will be described in equation 3.17 and out of that range will be described in equation 3.18. Total capital cost of single stage chiller will be described in equation 3.19.

$$B_{2s} = 500 \times \dot{Q}_{ch} \times \frac{130}{100}\ US\$ \qquad (3.17)$$

Where,

B_{2s} : Total capital cost of two stage vapour absorption chiller from 350 tons – 1000 tons in US\$

$\dot{Q}_{ch}$: Cooling capacity of vapour absorption chiller in $tons$

$$B_{2so} = 550 \times \dot{Q}_{ch} \times \frac{130}{100}\ US\$ \qquad (3.18)$$

Where,

B_{2s0} : Total capital cost of two stage absorption chiller out of rage of 350 tons – 1000 tons in US\$

$\dot{Q}_{ch}$: Cooling capacity of vapour absorption chiller in $tons$

$$B_{1s} = 350 \times \dot{Q}_{ch} \times \frac{130}{100}\ US\$ \qquad (3.19)$$

Where,

B_{1s} : Total capital cost of single stage vapour absorption chiller in $US\$$

$\dot{Q}_{ch}$: Cooling capacity of vapour absorption chiller in $tons$

3.5 Mathematical modelling for optimized energy extracted per unit cost

In Analysis of data, it was followed the similar way done in LP heaters Analysis. But in this vapour absorption chillers analysis it had several independent variables so that it must needed to check the multicollinearity of the independent variables. And also optimum solutions were generated using fitted models for two possible combination of options, called options 01 & 02 (Table 3.9) separately by using statistical software named MINITAB.

Table 3.9: Possible combinations of equipment for analysis

Option	Combination
Option 01	LP heat exchanger and two stage vapour absorption chiller series arrangement
Option 02	LP heat exchanger and single stage vapour absorption chiller series arrangement

Both options are considered because analysis is focused on both energy and cost. Option 02 system is deals with low cost comparatively relevant option 01 system.

Multicollinearity of the independent variables

Since there were four independent variables, it was checked for multicollinearity between the considered independent variables. For this Pearson correlation matrix were obtained for both option 01 & 02 data using statistical software. Also Variance Inflation factor was used to measure that multicollinearity of data were influence to the prediction done by fitted model or not.

Pearson Correlation Coefficient

Pearson correlation coefficient is a statistical measure of the strength of a monotonic relationship between paired data. Correlation values are changed between range which given by equation 3.20

$$-1 \leqslant r_s \leqslant 1 \qquad (3.20)$$

The strength of the correlation is described using the following guide (Table 3.10) for the absolute value of r_s.

Table 3.10: Strength description of the correlation

Value	Strength
0.00 - 0.19	very weak
0 .20 - 0.39	weak
0.40-0.59	moderate
0.60-0.79	strong
0.80-1.0	very strong

For a sample of size *n*, the *n* raw scores X_i, Y_i are converted to ranks rgX_i , and rgY_i can be computed by using equation 3.21.

$$r_s = \frac{Cov(rg_x\,, rg_y)}{\sigma_{rg_x}\sigma_{rg_y}} \qquad (3.21)$$

Where,

$Cov(rg_x\,, rg_y)$: Covariance of the variables

$\sigma_{rg_x}\sigma_{rg_y}$: Standard deviation of the variables

Variance Inflation Factor (VIF)

The variance inflation factor allows a quick measure of how much a variable is contributing to the standard error in the regression. When significant multicollinearity issues exist, the variance inflation factor will be very large for the variables involved.

$$VIF = \frac{1}{\left(1 - R^2(x_1)\right)} \tag{3.22}$$

Where,

R^2: R-Square value

Finally using fitted models for both options optimum solution has been obtained using statistical software in order to identify the minimum capital cost per energy unit and selected the best option.

3.6 Thermodynamic and economic analysis for waste heat recovery at standard CBD rate

Waste heat availability and recovering options and methodology have discussed in previous sections and related thermodynamic analysis are discussed in this section. Due to recovery of waste heat from boiler CBD system, total energy required to heat deaerator at saturated condition was reduced and therefore assumed that reduced steam for deaerator heating occurred from #4 extraction steam line and that amount of steam was consumed by remaining part of the turbine expansion process. Both deaerator supply steam and LP turbine inlet steam was supplied by IP turbine and therefore assumed that, there were no further work on IP turbine by reduced amount of bleed steam due to almost equal thermal conditions of both steam lines.

Hence, work done by turbine, increment of power generation and Investment based economic analysis are carried out in step wise.

Following data collected in order to thermodynamic analysis,

Table 3.11: Collected data of steam for thermodynamic analysis

Sampling point	**Pressure MPa(a)**	**Temperature ^{0}C**	**Condition**
Deaerator outlet	0.87	171.0	Saturated
LP turbine inlet steam	0.96	350.0	Superheated
LP turbine exhaust steam	-0.093	39.0	Condensing

Following data collected from *G. F.* C. Rogers and **Y.** R. Mayhew, Fifth Edition Thermodynamic and Transport Properties of Fluids book.

Table 3.12: Thermodynamic properties collected from steam Table

Property	**Symbol**	**Deaerator outlet**	**LP turbine exhaust steam**
Enthalpy(kJ/kg)	h(l) h(fg) h(g)	736.4 2,036.1 2,772.5	163.0 2,409.0 2,572.0
Entropy(kJ/kg.K)	S(l) S(fg) S(g)	N/R N/R 6.635	0.559 7.715 8.274

LP turbine inlet superheated steam enthalpy = 3,158 kJ/kg
LP turbine inlet superheated steam entropy = 7.301 kJ/kg.K

LP turbine exhaust condensing steam quality (x) was calculated by using equation 3.23.

$$S_{ex\ isen} = S_f + (x\ S_{fg}) \qquad (3.23)$$

Where,

$S_{ex\ isen}$: Entropy of LP turbine exhaust steam in isentropic condition
S_f : Entropy of condensed water at LP turbine exhaust pressure
S_{fg} : Entropy of saturated vapour at LP turbine exhaust pressure

For isentropic expansion,
$S_{ex\ isen}$= LP turbine inlet superheated steam entropy = 7.301 kJ/kg.K

Then enthalpy at isentropic expansion of LP turbine was calculated based of equation 3.24.

$$h_{ex\ isen} = h_f + (x\ h_{fg}) \qquad (3.24)$$

Where,

$h_{ex\ isen}$: Enthalpy of LP turbine exhaust steam in isentropic condition

h_f : Enthalpy of condensed water at LP turbine exhaust pressure

h_{fg} : Enthalpy of saturated vapour at LP turbine exhaust pressure

Reduction amount of extraction steam which was expanded through LP turbine was calculated by using equation 3.25.

$$\text{Reduction of \#4 extraction steam}(\dot{M}_4) = \frac{Q_h}{(h_{LP\ i} - h_{D\ l})}\ \text{kg/s} \qquad (3.25)$$

Where,

Q_h : Energy extracted by introduced LP heater

$h_{LP\ i}$: Enthalpy of LP turbine inlet steam

$h_{D\ l}$: Enthalpy of saturated water in deaerator

LP turbine exhaust enthalpy calculated by using 90% isentropic efficiency for LP turbine. Equation 3.26 used for calculation.

$$h_{ex\ real} = h_{LP\ i} - \{\eta_{isen}(h_{LP\ i} - h_{ex\ isen})\} \qquad (3.26)$$

Where,

$h_{ex\,real}$: Enthalpy of LP turbine exhaust steam in real condition at 90% isentropic efficiency
η_{isen} : Isentropic efficiency of LP turbine

Power output increment from all three units base on LP heater was calculated by equation 3.27.

$$P_e \ = 3 \ \times \dot{M}_4 (h_{LP\,i} - h_{ex\,real}) \times \eta_G \tag{3.27}$$

Where,
P_e : Power output increment
η_G : Generator efficiency

Annual income was calculated for 20 years by taking 90% plant factor and 17.60 Rs/kWh as a tariff for the electric energy sales. Capital cost values and annual cost values are used to calculate NPV and IRR for different cases based on LP heater outlet waste heat fluid temperature. Other expenses are neglected because there are already appointed staff and heaters are usually not dealing with consumable parts.

Due to operation of vapour absorption chiller, electric power requirement for the vapour compression chillers are reduced and therefore, energy selling potential increased. Energy selling which is based on reduction of electric power consumption was calculated and annual income for 20 years has calculated by using COP of existing chillers as 3.0 and 17.60 Rs/kWh as energy selling price. Plant factor was taken as 90% as previous.

$$P_m \ = \frac{\dot{Q}_{ch}}{(COP_c \times \eta_m)} \tag{3.28}$$

Where,

P_m : Motor power saving

$\dot{Q}_{ch}$: Cooling capacity of vapour absorption chiller

η_m : Vapour compression chiller motor efficiency

COP_c : Coefficient of performance of vapour compression chillers

η_m= 95%

As previous sections, considered combined systems as option 01 and option 02 combinations and analysed those combined systems for NPV and IRR to identify best economical combination.

4 RESULTS AND DISCUSSION

4.1 Waste heat availability from boiler blowdown system in different CBD rates

Calculated data of flash steam recovered by boiler CBD flash tank, waste heat fluid mass flow rate availability for both one boiler and three boiler cases and waste heat availabilities in both one boiler and three boiler cases with respect to different boiler CBD rates calculated and summarized in Figure 4.1 as follows.

Table 4.1: Summarized data of waste heat availability

Boiler CBD rate of one unit (kg/h)	**Flash steam recovered by one CBD flash tank (kg/h)**	**Waste heat fluid mass flow rate from CBD flash tank (kg/h)**		**Waste heat availability (kW)**	
		one unit	**three units**	**one unit**	**three units**
10,250	4,538	5,712	17,136	1,316.9	3,950.7
15,375	6,807	8,568	25,704	1,975.3	5,926.0
20,500	9,076	11,424	34,272	2,633.8	7,901.3
25,625	11,345	14,280	42,840	3,292.2	9,876.2
30,750	13,614	17,136	51,408	3,950.7	11,852.0

According to the Table 4.1 results, it is observed that flash steam recovery amount by CBD flash tank, waste heat fluid mass flow rate and waste heat availability were increased with boiler CBD rate and waste heat availability has increased from 3.95 MW to 11.85 MW for different CBD rates.

Waste heat availability was quite significant and therefore, analysed for energy saving technologies in terms of energy extraction per unit capital cost and results are concluded in next subsections.

4.2 Results of the energy recovery opportunities

According to Figure 3.1, has identified the opportunity to introduce new indirect type low pressure heat exchanger to preheat condensate water by using waste heat discharged by CBD flash tank as saturated water at 1.4 MPa and 198 ^{0}C. It was observed that, maximum waste heat energy can be extracted by this new LP heater, if it is located between gland steam condenser (GC) and LP heater Number 08 (HTR-8).

Identified second opportunity, which can be able to run the vapour absorption chiller to either fully or partially replace electrically driven vapour compression chillers for air conditioning systems in power plant premises.

Then, identified the opportunities of those two system separately and combining for waste heat extraction and therefore, introduced layout to analyse energy extraction at different conditions. Therefore introduced new layout for boiler blowdown system and shown in Figure 3.3 and Figure 3.5.

Furthermore, identified the applicability of both single stage and two stage vapour absorption chillers for these kind of systems and therefore, analysis were done using both type of absorption chillers.

4.2.1 Energy and cost analysis for standard CBD flow rate

Therefore, analysis of total energy extraction capabilities in all three boilers of different individual systems at standard CBD rate, energy extraction capabilities of combined systems at standard CBD rate and total cost and energy extracted per unit cost variation in combined systems at standard CBD rate are concluded in Figure 4.1 Figure 4.2 and Figure 4.3 respectively.

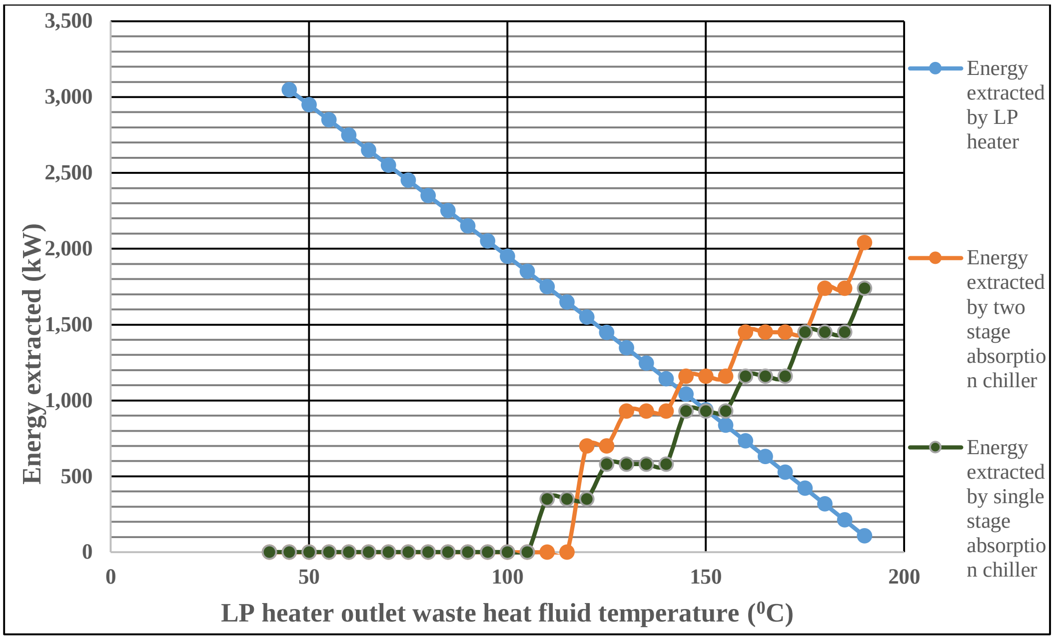


Figure 4.1: Energy extraction capabilities of different individual systems at standard CBD rate

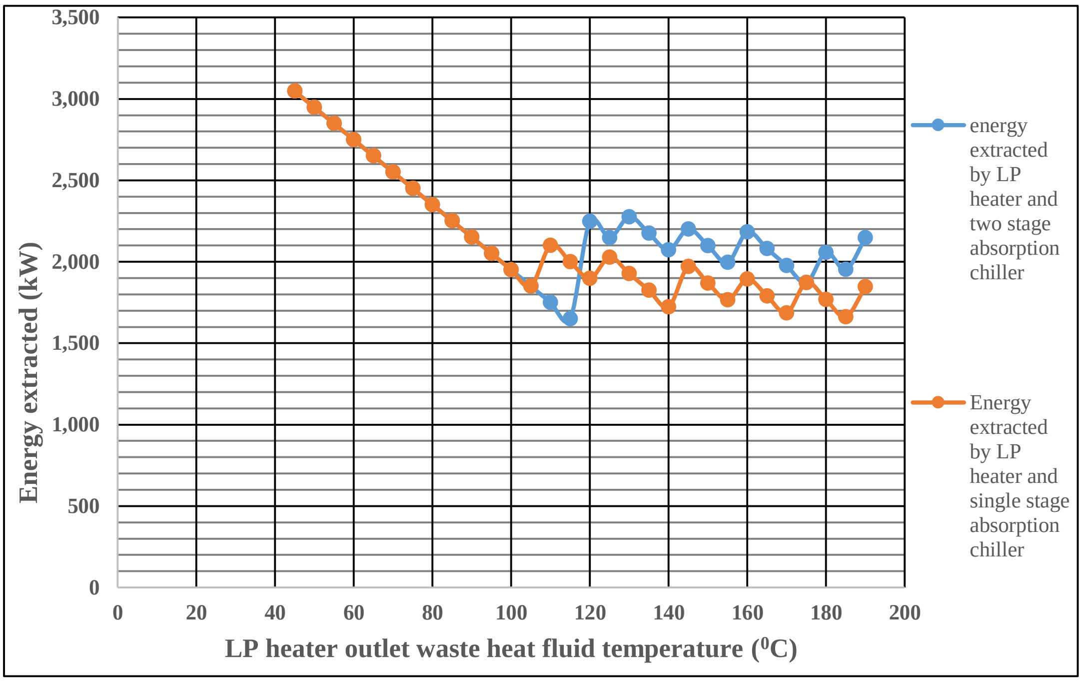


Figure 4.2: Energy extraction capabilities of combined systems at standard CBD rate

According to the Figure 4.1 total energy extraction capability is high in LP heaters than the single stage or two stage vapour absorption chillers when considered individually. In addition to that, amount of heat extracted of LP heaters are linearly varying with LP heater outlet waste heat fluid temperature.

In contrast, cooling capacities of vapour absorption chillers are significant only when waste heat water temperature on or above at 110 ^{0}C for single stage and 120 ^{0}C for two stage which are depend on the hot water mass flow rate because of minimum required mass flow are available above mentioned values of inlet temperature by mixing appropriate amount of chiller plant outlet water. Absorption chillers cooling capacities are increasing with LP heater outlet waste heat fluid temperature. But, cooling capacity of two stage vapour absorption chillers is higher than single stage chiller in most cases. Therefore, it can be concluded that, heat exchangers are operating at higher efficiencies than the single effect, single stage or two stage vapour absorption chillers.

In Figure 4.2, total energy extraction capability variation of combined systems at standard CBD mass flow rate have represented and observed that chiller plants are significant at LP heater outlet temperatures are on or higher at 110 ^{0}C and zigzag variation can be observed due to effect of both systems. Even though, heat exchangers can be extracted 3,048 kW, two stage and single stage chillers with or without presence in heat exchangers are extracted only 1,900-2,400 kW and 1,700-2,200 kW respectively.

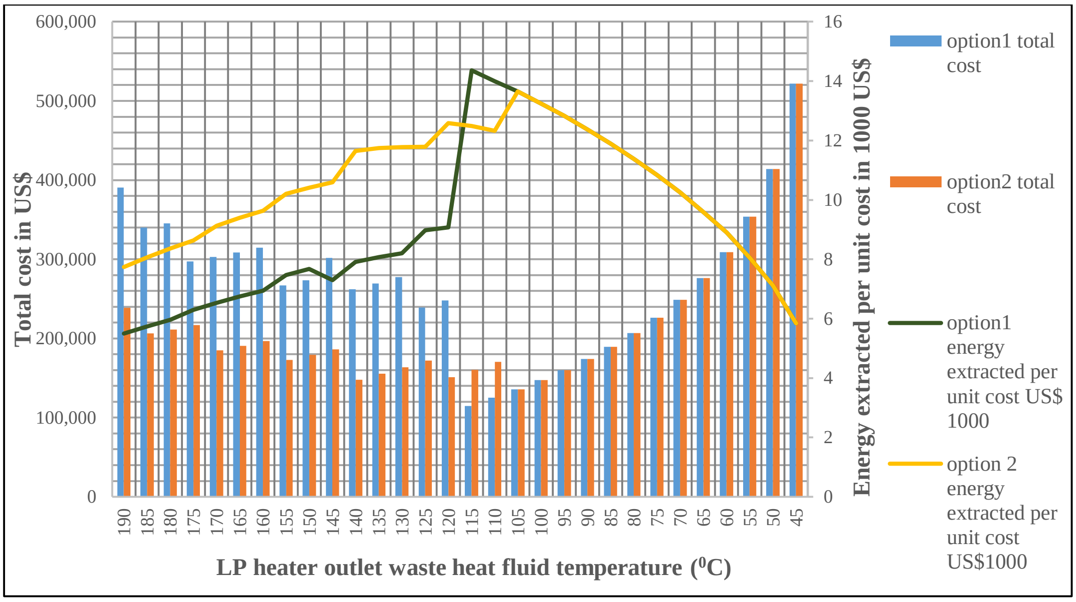


Figure 4.3: Total cost and energy extracted per unit cost variation in combined systems at standard CBD rate

Total capital cost variation and energy extracted per unit capital cost variation in combined systems at standard CBD rate have plotted in Figure 4.3 and it can be observed that total capital cost variation is going through minimum point in both option 01 and potion 02 systems and cost at lower temperatures than 110 ^{0}C are only affect from LP heaters and cost is drastically increasing when temperature decreasing which is lower than 110 ^{0}C.

Due to complexity of two stage vapour absorption chillers, capital cost is much higher than single stage machines and that can be observed in higher temperature values than 110 ^{0}C. Therefore, it can be concluded that single stage machines with LP heaters are the cheaper in capital cost at 150 ^{0}C and 105 ^{0}C temperatures. However, total capital cost of two stage machines with LP heaters are going through minimum point at 115 ^{0}C temperatures.

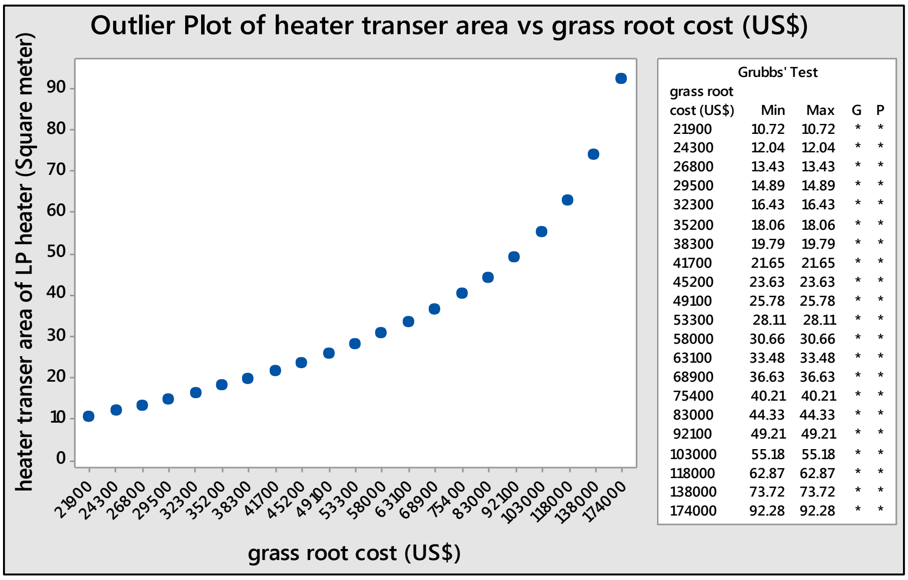
Energy extracted per unit capital cost at standard CBD mass flow rate also running in maximum point in both options and can be observed peak points of single stage machine with LP heater are at 105 ^{0}C temperatures while two stage machine with LP heater are at 115 ^{0}C temperatures. Energy extraction capacities and capital cost values of optimized points can be summarized in Table 4.2.

Table 4.2: Energy extraction capacities and capital cost values of optimized points at standard CBD mass flow rate

Parameter	**Option 01 optimum data at standard CBD rate**	**Option 02 optimum data at standard CBD rate**
CBD flow rate (kg/h)	10,250	10,250
LP heater outlet temperature (^{0}C)	115 ^{0}C	105 ^{0}C
Heating capacity (kW)	1650	1851
Total energy (kW)	1650	1851
LP heaters cost (US$)	114,900	135,600
Total cost (US$)	114,900	135,600
Energy per unit cost (kW/US$ 1000)	14.36	13.65

Capital (grass root) cost model

Results of the capital cost model is summarized in this section. Outlier plot of heat transfer area against grass root cost and grass root cost variation against heat transfer area of LP heater is summarized in Figure 4.4 and Figure 4.5.



Grubbs' Test

grass root cost (US$)	Min	Max	G	P
21900	10.72	10.72	*	*
24300	12.04	12.04	*	*
26800	13.43	13.43	*	*
29500	14.89	14.89	*	*
32300	16.43	16.43	*	*
35200	18.06	18.06	*	*
38300	19.79	19.79	*	*
41700	21.65	21.65	*	*
45200	23.63	23.63	*	*
49100	25.78	25.78	*	*
53300	28.11	28.11	*	*
58000	30.66	30.66	*	*
63100	33.48	33.48	*	*
68900	36.63	36.63	*	*
75400	40.21	40.21	*	*
83000	44.33	44.33	*	*
92100	49.21	49.21	*	*
103000	55.18	55.18	*	*
118000	62.87	62.87	*	*
138000	73.72	73.72	*	*
174000	92.28	92.28	*	*

Figure 4.4: Outlier plot of heat transfer area versus grass root (capital) cost

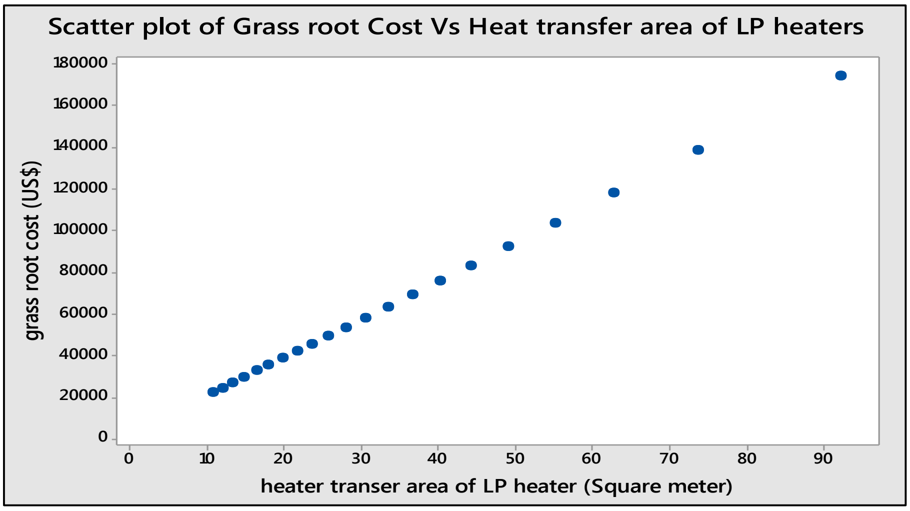


Figure 4.5: Graphical summary of grass root (capital) cost versus heater area

In Figure 4.4 and Figure 4.5 are described the distribution of data set using Scatterplot and Outlier plot. According to these figures, there is linear relationship between the grass roots cost and heater area and no outlier in the selected data set. According to the outlier plot there is a slight curve shape between the grass root cost and heater area. That means data set will be fit in to the simple linear regression model with polynomial equation.

Anderson Darling test results were summarized in Figure 4.6 and Figure 4.7, which are done for heat transfer area of LP heater and grass root cost respectively.

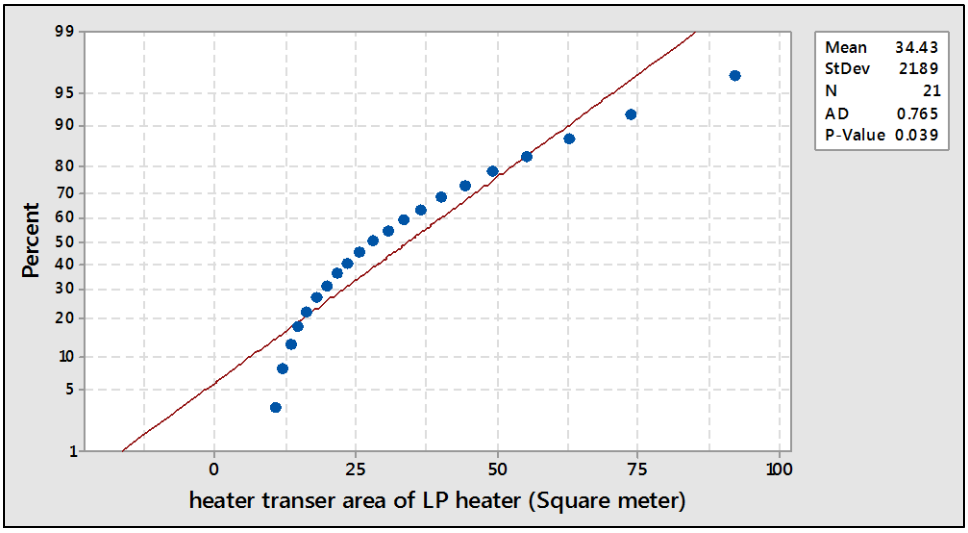


Figure 4.6: Probability plot of LP heater heat transfer area

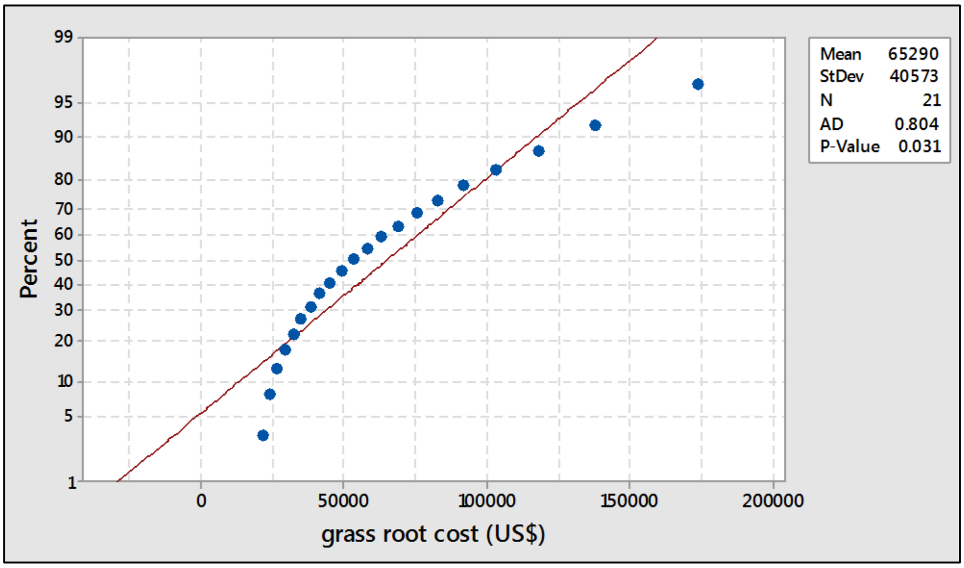


Figure 4.7: Probability plot of grass root cost

As per the graphs in Figure 4.6 and Figure 4.7 and p values given in both graphs shows that variables are normally distributed. Since both p values < 0.05(Significant level), Null hypothesis (i.e – data are normally distributed) is accepted.

4.3 Polynomial regression analysis for grass root (capital) cost versus heat transfer area

Polynomial regression model was fitted to dependent variable grass root cost and Independent variable heater area in order to predict the optimum solution for the grass root cost. Model is given by equation 4.1,

$$\text{Grass root cost} = 2853 + 1777\text{A} + 0.6308A^2 + 0.002318A^3 \quad (4.1)$$

Where,

A : Heat transfer area of LP heater in m^2

Standard deviation = 121.271

R-Square = 100%

R-Square (adj) = 100%

A 100% R-sq(adj) indicates that whenever observe a variation in the value of y, 100% of it is due to the model (or due to change in x) and 0% is due error or some unexplained factor. That is this data set fits well to the fitted model. In the Figure 4.8 shows the fitted line plot for regression model.

Analysis of Variance (ANOVA)

Analysis of variance Table obtained by regression model was used to compares the fits of different linear models, the F test can assess multiple coefficients simultaneously.

Table 4.3: Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	3.29E+10	1.10E+10	746235.8	0
Error	17	2.50E+05	1.47E+04		
Total	20	3.29E+10			

Since the P value for the F-test of overall significance test is less than significance level 0.05, it can reject the null-hypothesis and conclude that fitted model provides a better fit than the intercept-only model.

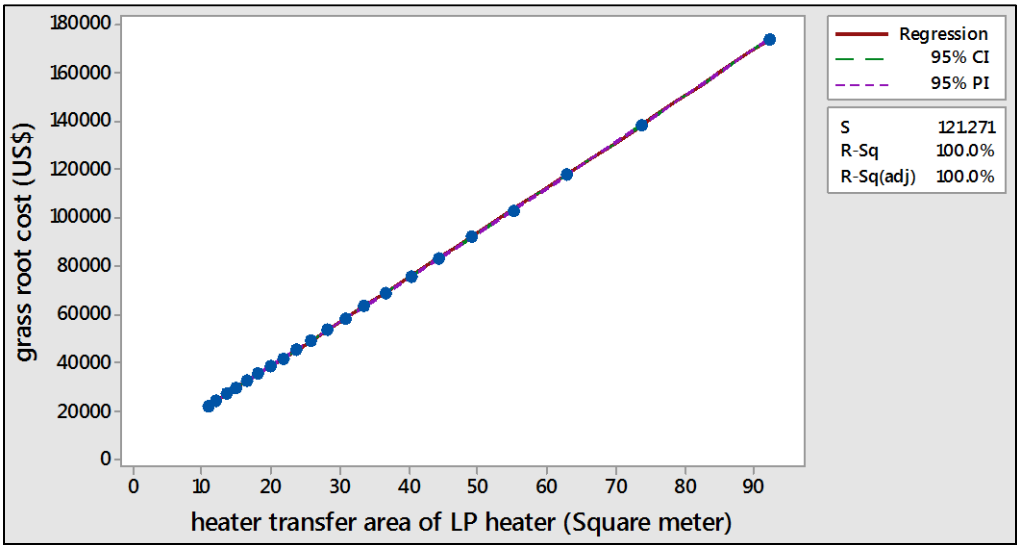


Figure 4.8: Fitted line plot for the regression model

According to the Figure 4.8, It could show that the fitted model is 100% align with the actual data as explained by R-square value.

Assumptions in Regression Analysis

Further checked results of the validity of Regression model assumptions using graphical represent of the residuals (Figure 4.9).

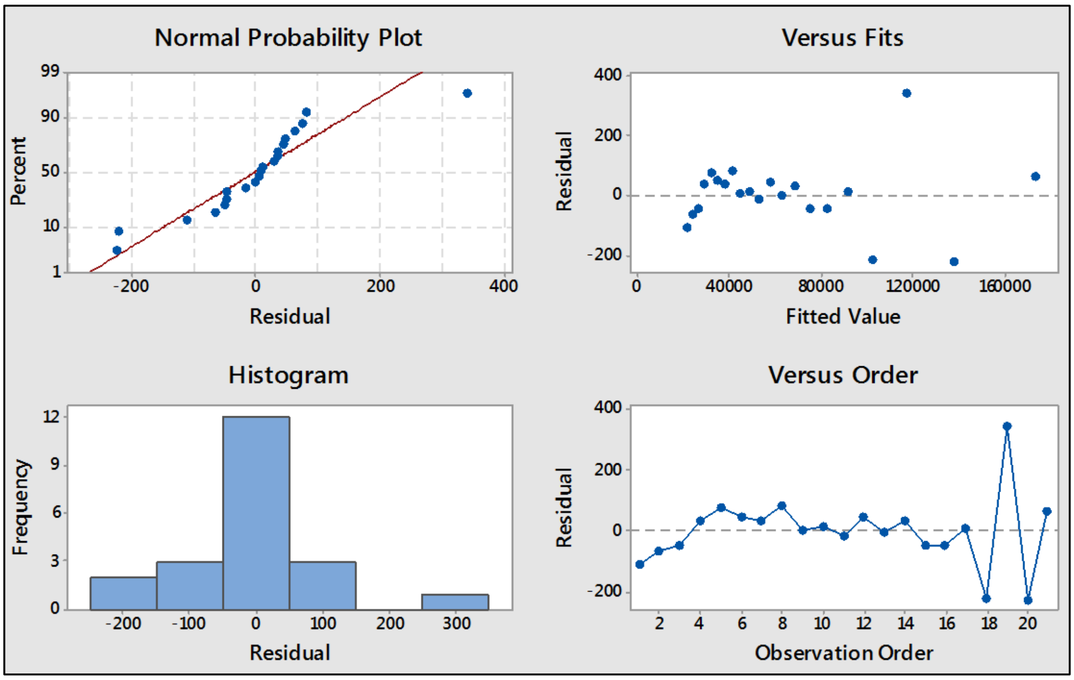


Figure 4.9: Graphical represent of the residuals

As per the normal probability plot graph in Figure 4.9 checks the assumption of normality of error terms. In this case it can see that most of the points are clustered around red line indication that the error terms are approximately normal. Thus assumption of normality is valid.

Versus fit graph in Figure 4.9 plots the error terms against the fitted values. There are approximately half of them are above and half are below the zero-line indicating that, assumption of error terms having mean zero is valid.

On the same graph it can see the error terms approximately linear, that indicating the assumption of independence of error.

The histogram graph in Figure 4.9 again re-emphasizes the normality assumption. Though sample size is just 21.

4.4 Energy and cost analysis for different CBD flow rates

Analysis results of total energy extraction capabilities of combined systems, total cost variations and energy extracted per unit cost variation of LP heater and vapour absorption chiller in series arrangement in both option 01 and option 02 systems are at different CBD mass flow rate were summarized in this section.

Figure 4.10 described total energy extracted in option 01 combination and there were two main independent variables named as, LP heater outlet temperature and boiler CBD mass flow rate.

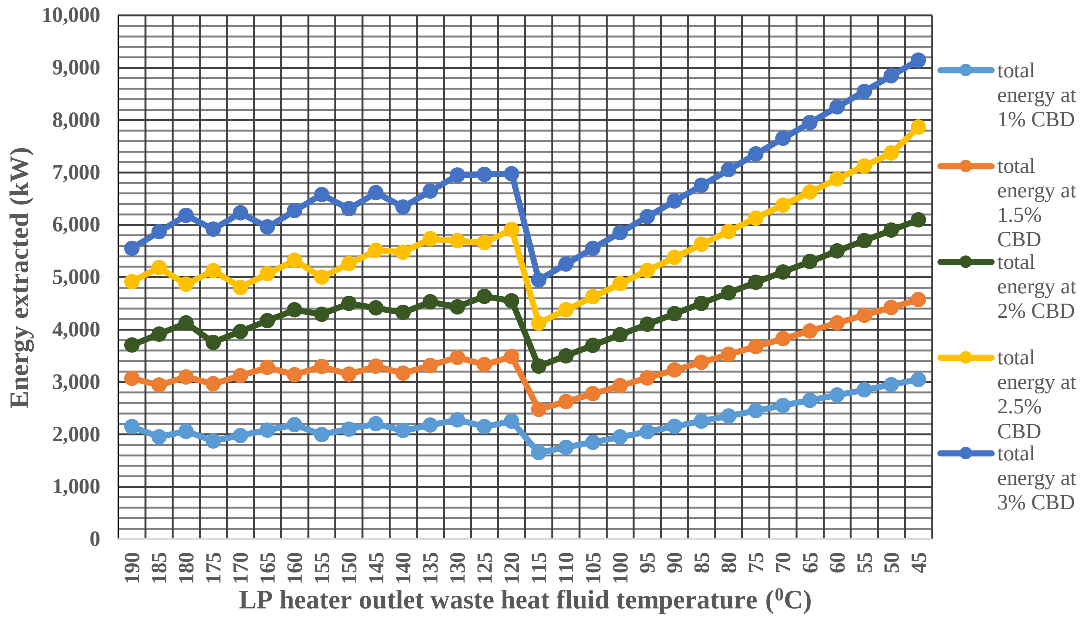


Figure 4.10: Total energy extracted in option 01 combination

According to the Figure 4.10, total energy extraction variation at different CBD mass flow rates were similar in pattern, but extracted energy amount is increased with CBD mass flow rate. Significance of two stage vapour absorption chiller is limited from 190 ^{0}C to 120 ^{0}C and total extracted energy has slightly increased when temperature decreasing. Sudden drop has occurred in total energy extracted in between 120 ^{0}C and 115 ^{0}C, because of available energy cannot be extracted by absorption chiller and it can be identified as a point of huge energy loss within the system. This loss is increasing with CBD mass flow rate. However, total energy extraction is linearly increased when temperature drops from 115 ^{0}C and only LP heater is responsible for that variation.

Figure 4.11 described total energy extracted in option 02 combination and there were two main independent variables named as, LP heater outlet temperature and boiler CBD mass flow rate.

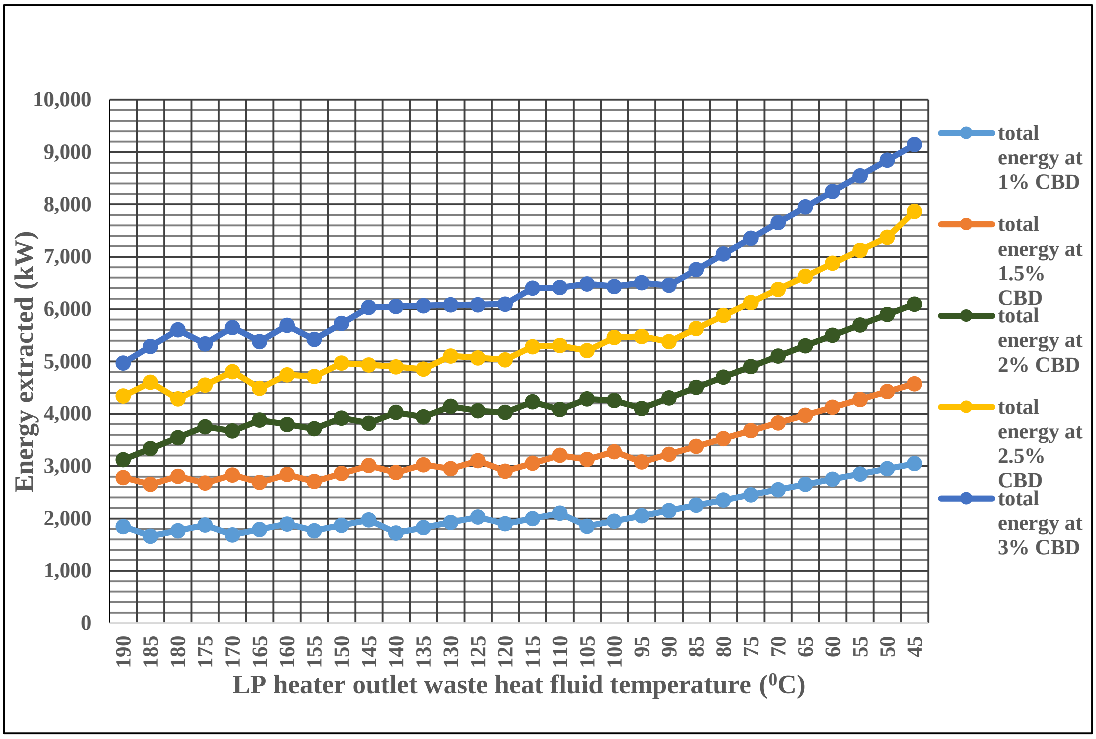


Figure 4.11: Total energy extracted in option 02 combination

According to the Figure 4.11, total energy extraction variation at different CBD mass flow rates were similar in pattern, but extracted energy amount is increased with CBD mass flow rate. Significance of single stage vapour absorption chiller is limited from 190 ^{0}C to 95 ^{0}C and cooling capacity of absorption machine is slightly increased when temperature decreasing. However, total energy extraction is linearly increased when temperature drops from 95 ^{0}C and only LP heater is responsible for that variation.

Figure 4.12 described total capital cost variation in option 01 combination and there were two main independent variables named as, LP heater outlet temperature and boiler CBD mass flow rate.

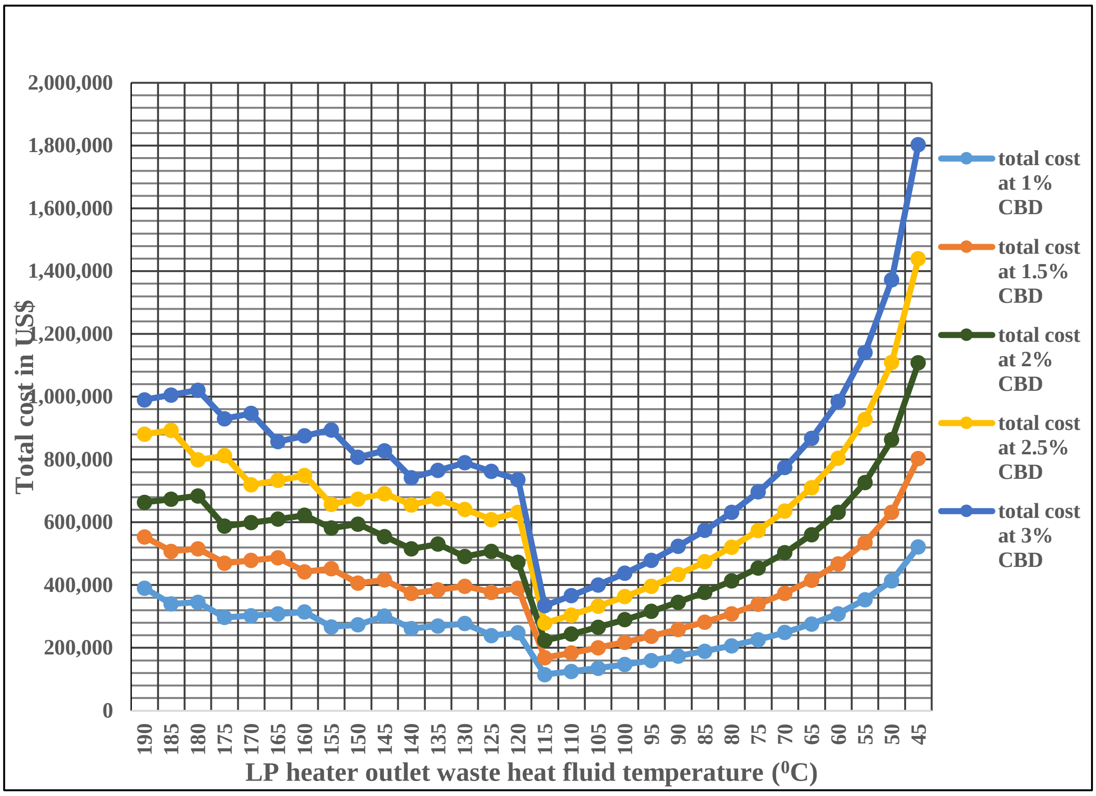


Figure 4.12: Total cost variation in option 01 combination

According to the Figure 4.12, total capital variation at different CBD mass flow rates were similar in pattern, but total capital cost amount is increased with CBD mass flow rate. Significance of two stage vapour absorption chiller is limited from 190 ^{0}C to 120 ^{0}C and total capital cost is decreasing when temperature falling. Sudden drop has occurred in total capital cost in between 120 ^{0}C and 115 ^{0}C, because of chiller capital cost become zero due to out of the range and it can be identified as a point of huge energy loss and lower capital cost within the system. However, total capital cost is drastically increased when temperature drops from 115 ^{0}C and only LP heater is responsible for that variation.

Figure 4.13 described total capital cost variation in option 02 combination and there were two main independent variables named as, LP heater outlet temperature and boiler CBD mass flow rate.

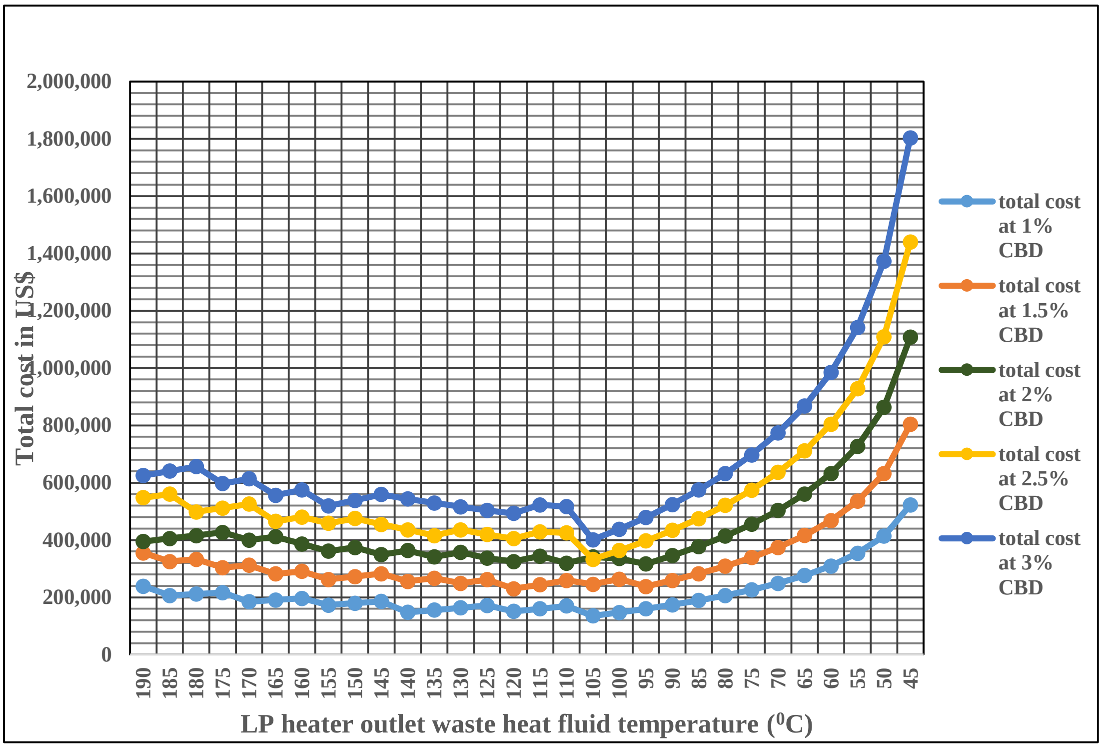


Figure 4.13: Total cost variation in option 02 combination

According to the Figure 4.13, total capital variation at different CBD mass flow rates were similar in pattern, but total capital cost amount is increased with CBD mass flow rate. Significance of single stage vapour absorption chiller is limited from 190 ^{0}C to 95 ^{0}C and total capital cost is slightly decreasing when temperature falling. There are no any significance of chiller that temperature lower than the 95 ^{0}C and therefore, chiller capital cost become zero. However, total capital cost is drastically increased when temperature drops from 95 ^{0}C and only LP heater is responsible for that variation. Figure 4.14 described energy extracted per unit capital cost in option 01 combination.

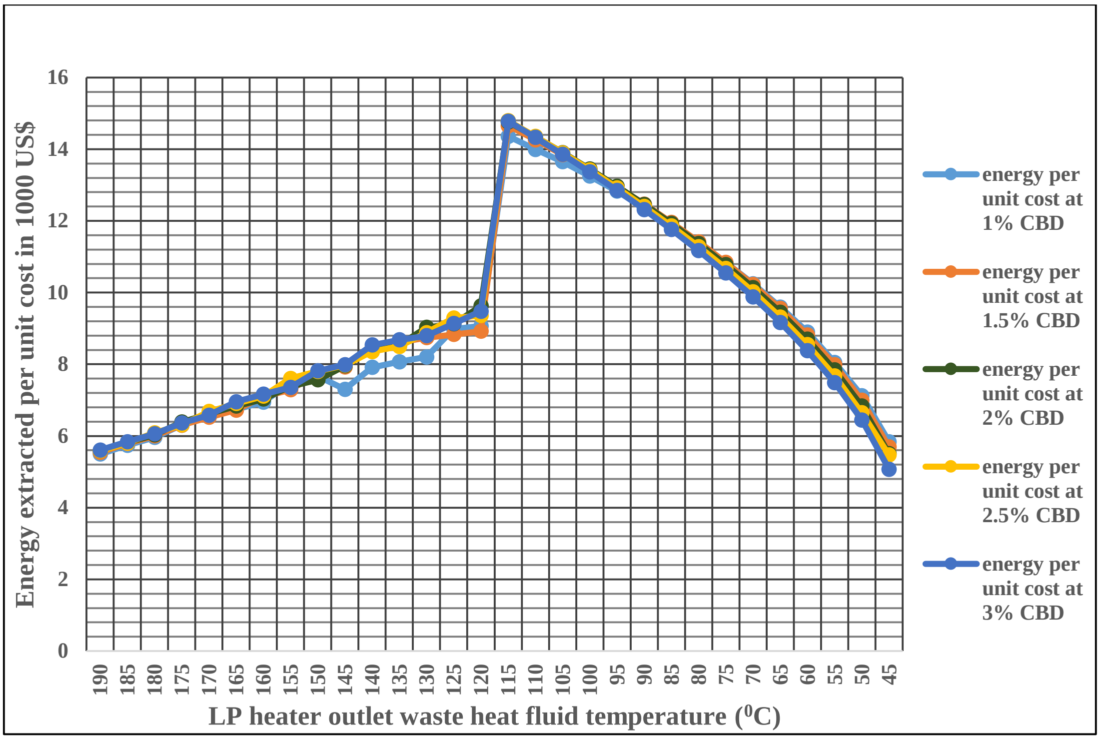


Figure 4.14: Energy extracted per unit capital cost in option 01 combination

According to the Figure 4.14, energy extracted per unit capital cost in option 01 combination at different CBD mass flow rates were similar in pattern. Although extracted energy amount is slightly lower in 1%BMCR CBD mass flow rate, other variations are almost similar. Significance of two stage vapour absorption chiller is limited from 190 ^{0}C to 120 ^{0}C and energy extracted per unit capital cost has increased from 5 kW/US$1000 to 10 kW/US$1000 when temperature decreasing. Sudden increase has occurred in energy extracted per unit capital cost in between 120 ^{0}C and 115 ^{0}C, because of absorption chiller is insignificant and therefore, cost is only relate with LP heater. However, energy extracted per unit capital cost is drastically decreased when temperature drops from 115 ^{0}C and only LP heater is responsible for that variation. Figure 4.15 described energy extracted per unit capital cost in option 02 combination.

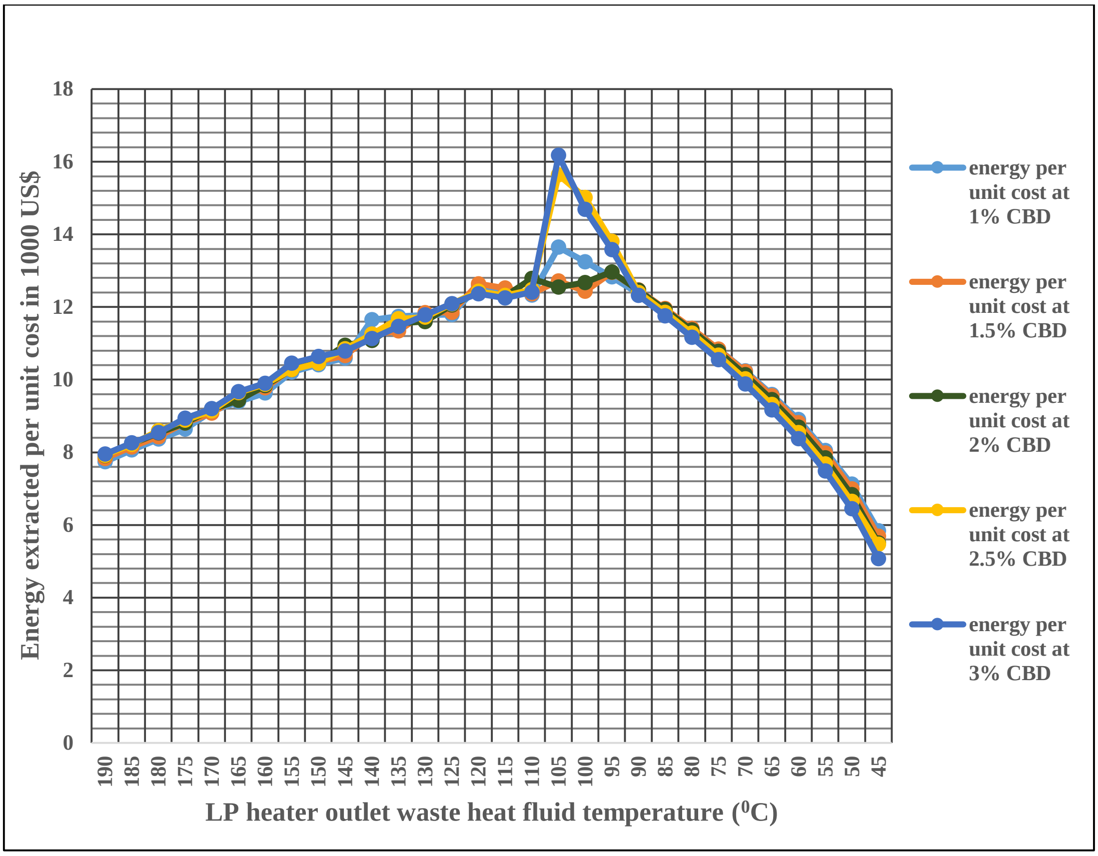


Figure 4.15: Energy extracted per unit capital cost in option 02 combination

According to the Figure 4.15, energy extracted per unit capital cost in option 02 combination at different CBD mass flow rates were similar in pattern with small deviations in higher CBD levels. Although extracted energy amount is slightly lower in 1% BMCR CBD mass flow rate, other variations are almost similar. Significance of single stage vapour absorption chiller is limited from 190 ^{0}C to 95 ^{0}C and energy extracted per unit capital cost varied from 8 kW/US$1000 to 16 kW/US$1000 when temperature decreasing. Sudden spike has observed in energy extracted per unit capital cost in between 110 ^{0}C and 90 ^{0}C for higher CBD values. However, energy extracted per unit capital cost is drastically decreased when temperature drops from 90 ^{0}C and only LP heater is responsible for that variation.

4.5 Regression model for energy extracted per unit capital cost

In this section results and findings of the research will be discussed related to the Vapour absorption chillers analysis. In this study it was compared the two options related to vapour absorption chillers Option 01 & 02. In this case dependent variable for both case is Energy per unit cost and considered four independent variables such that, heat exchanger outlet temperature, blowdown rate, energy extracted by heat exchange and energy extracted by chiller.

Table 4.4: Descriptive statistics

Variable	**Option 01**						
	No. of Observation	**Mean**	**Mean of the Standard Error**	**Standard Deviation**	**Min**	**Med**	**Max**
heat exchanger outlet temperature(T1)	150	117.5	3.55	43.42	45	117.5	190
blowdown rate	150	20.51	0.594	7.279	10.25	20.5	30.75
energy extracted by heat exchanger	150	3184	178	2180	107	2763	9145
energy extracted by chiller	150	1288	125	1529	0	350	5230
total energy extracted per unit capital cost	150	9.698	0.23	2.82	5.236	9.013	15.693
Variable	**Option 02**						
	No. Of Observation	**Mean**	**Mean of the Standard Error**	**Standard Deviation**	**Min**	**Med**	**Max**
heat exchanger outlet temperature(T1)	150	117.5	3.55	43.42	45	117.5	190
blowdown rate	150	20.51	0.594	7.279	10.25	20.5	30.75
energy extracted by heat exchanger	150	3184	178	2180	107	2763	9145
energy extracted by chiller	150	1146	103	1261	0	755	4650
total energy extracted per unit capital cost	150	11.199	0.18	2.2	5.236	11.322	16.925

As per the Table 4.4, there is considerable variation of both option 01 & option 02 variables which need to analysed in statistically.

Normality Test

Since data set includes 150 observations, Normality of the data set is not effecting for the regression model.

Spearmen Correlation metrics

Spearmen correlation matrix Tables was obtained for both options separately to check the multicollinearity of the independent variables.

Table 4.5: Correlation matrix

Option 01 correlation matrix	**Heat exchanger outlet temperature (T_1)**	**CBD rate**	**Energy extracted by heat exchanger**	**Energy extracted by chiller**
blowdown rate	0			
energy extracted by heat exchanger	-0.806	0.518		
energy extracted by chiller	0.841	0.299	-0.608	
energy extracted per unit capital cost	-0.366	-0.028	0.284	-0.61

Option 02 correlation matrix	**Heat exchanger outlet temperature (T_1)**	**CBD rate**	**Energy extracted by heat exchanger**	**Energy extracted by chiller**
blowdown rate	0			
energy extracted by heat exchanger	-0.806	0.518		
energy extracted by chiller	0.856	0.343	-0.6	
energy extracted per unit capital cost	0.169	-0.079	-0.153	-0.111

According to the Table 4.5, There are bit high correlation is existing between Heat exchanger outlet temperature with energy extracted by chiller and energy extracted by heat exchanger in both options.

Regression Analysis

Separate regression models were fitted for both options 01 & 02 in order to optimize energy extracted per unit capital cost and select the best option.

Table 4.6: Analysis of Variance

Option 01					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	4	1026.63	256.658	235.43	0
energy extracted by chiller	1	866.97	866.969	795.25	0
energy extracted by heat exchanger	1	362.68	362.676	332.67	0
blowdown rate	1	483.93	483.927	443.89	0
heat exchanger outlet temperature(T1)	1	14.1	14.103	12.94	0
Error	145	158.08	1.09		
Total	149	1184.71			

Option 02					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	4	554.08	138.521	120.41	0
energy extracted by chiller	1	523.72	523.72	455.24	0
energy extracted by heat exchanger	1	279.68	279.68	243.11	0
blowdown rate	1	347.51	347.51	302.07	0
heat exchanger outlet temperature(T1)	1	10.69	10.687	9.29	0.003
Error	145	166.81	1.15		
Total	149	720.89			

Since the P value for the both F-test of overall significance test is less than significance level 0.05, It can reject the null-hypothesis and conclude that fitted models provides a better fit than the intercept-only model.

Table 4.7: Regression model & Model summary

Option 01				
Regression model	$\mathrm{Y} = 12.42 - 0.004639\mathrm{E_C} - 0.00333\mathrm{E_{HX}} + 0.7972\dot{\mathrm{M}} - 0.02125\mathrm{T_1}$ 4.2			
Model Summary	**S**	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
	1.04412	86.66%	86.29%	85.43%
Option 02				
Regression model	$\mathrm{Y} = 9.073 - 0.006284\mathrm{E_C} - 0.003610\mathrm{E_{HX}} + 0.9092\dot{\mathrm{M}} + 0.01850\mathrm{T_1}$ 4.3			
Model Summary	**S**	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
	1.07257	76.86%	76.22%	74.86%

Where,

Y : Total energy extracted per unit capital cost in $kW/US\$1000$

E_C : Energy extracted by chiller in kW

E_{HX} : Energy extracted by heat exchanger in kW

$\dot{M}$: Boiler CBD rate in kg/h

T_1 : LP heater outlet waste heat fluid temperature in ℃

In Table 4.7 shows that regression models and model summary for both option 01 & 02. As per the summary of model both models are well fitted with R-square (adj) is 86% and 76% both option 01 & Option 02 respectively.

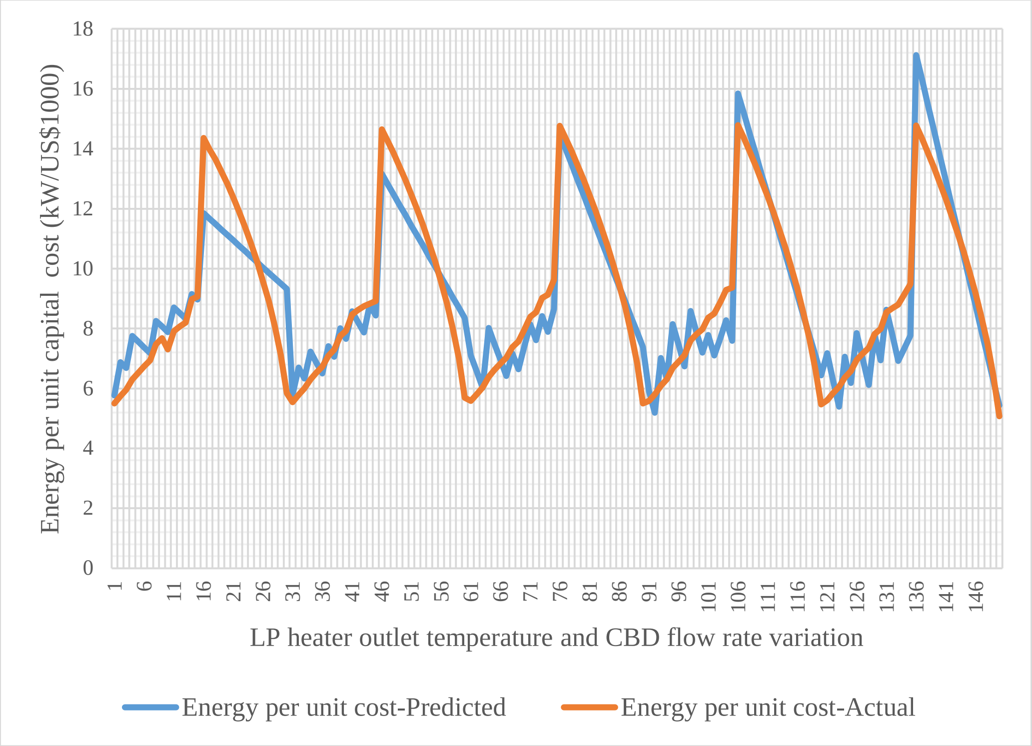


Figure 4.16: Actual vs Predicted values of model in option 01 combination

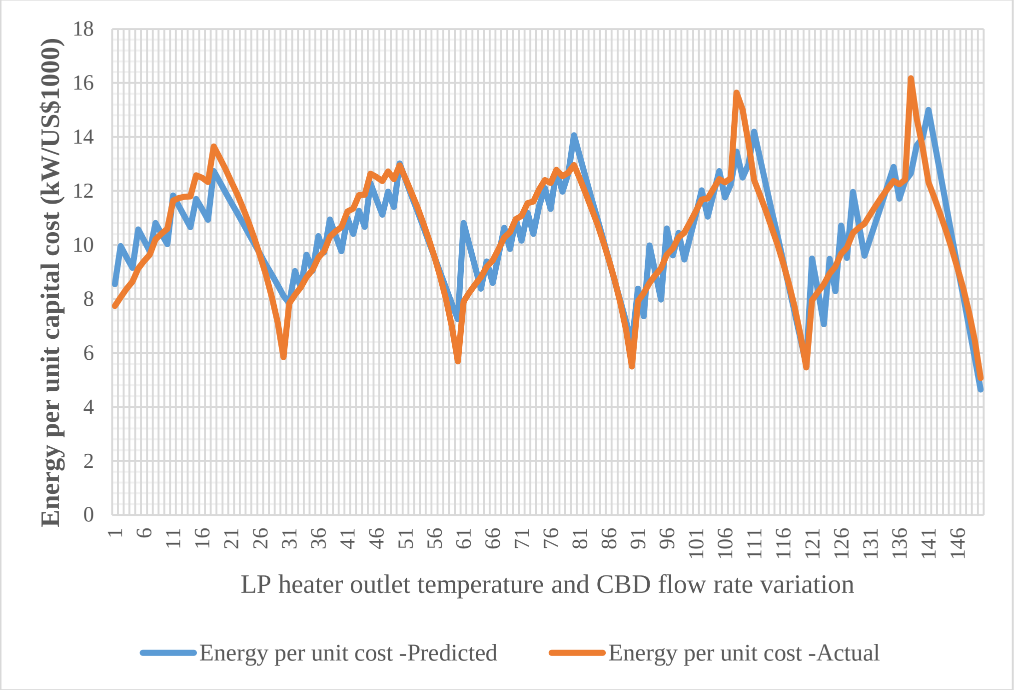


Figure 4.17: Actual vs Predicted values of model in option 02 combination

In Figure 4.16, Figure 4.17 shows that actual data vs Predicted data for both model of option 01 and option 02. As per this graphs model is well fitted with actual data.

Assumptions in Regression Analysis

Further check the validity of Regression model assumptions using graphical represent of the residuals (Figure 4.18).

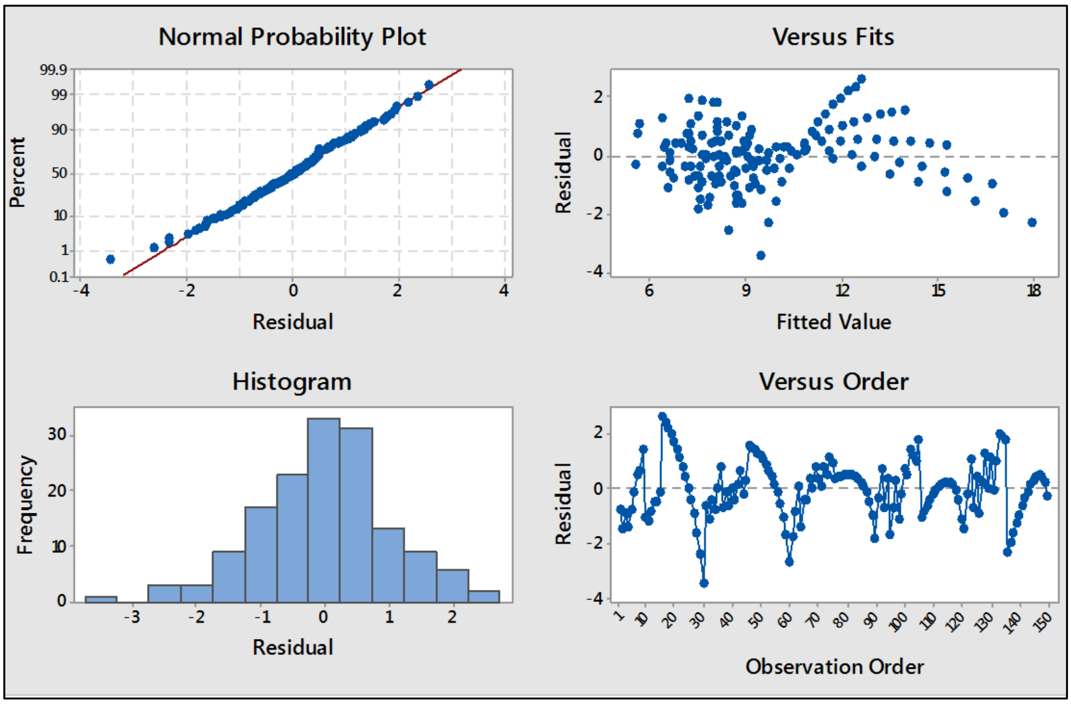


Figure 4.18: Residual plots for option 01 regression model

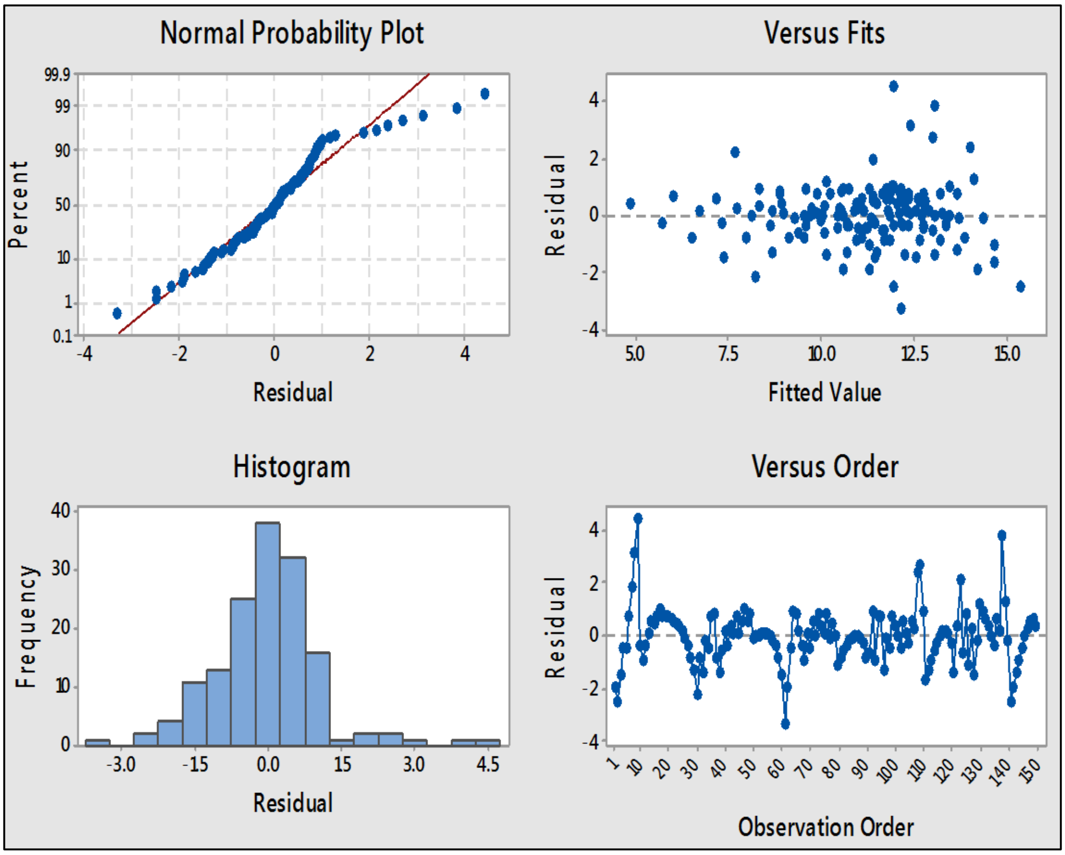


Figure 4.19: Residual plots for option 02 regression model

As per the graph on left top checks the assumption of normality of error terms. In this case it can see that most of the points are clustered around red line indication that the error terms are approximately normal. Thus assumption of normality is valid.

The graph on right top plots the error terms against the fitted values. There are approximately half of them are above and half are below the zero-line indicating that, assumption of error terms having mean zero is valid.

On the same graph it can see the error terms approximately linear, that indicating the assumption of independence of error.

The bottom left graph again re-emphasizes the normality assumption

4.6 Thermodynamic and economic analysis results at standard CBD rate

Analysis results of total power generation increment of combined systems, total annual income, NPV and IRR variation in both option 01 and option 02 systems are at standard CBD mass flow rate were summarized in this section.

Figure 4.20 described effect of total selling power increment in both combinations at boiler standard CBD mass flow rate.

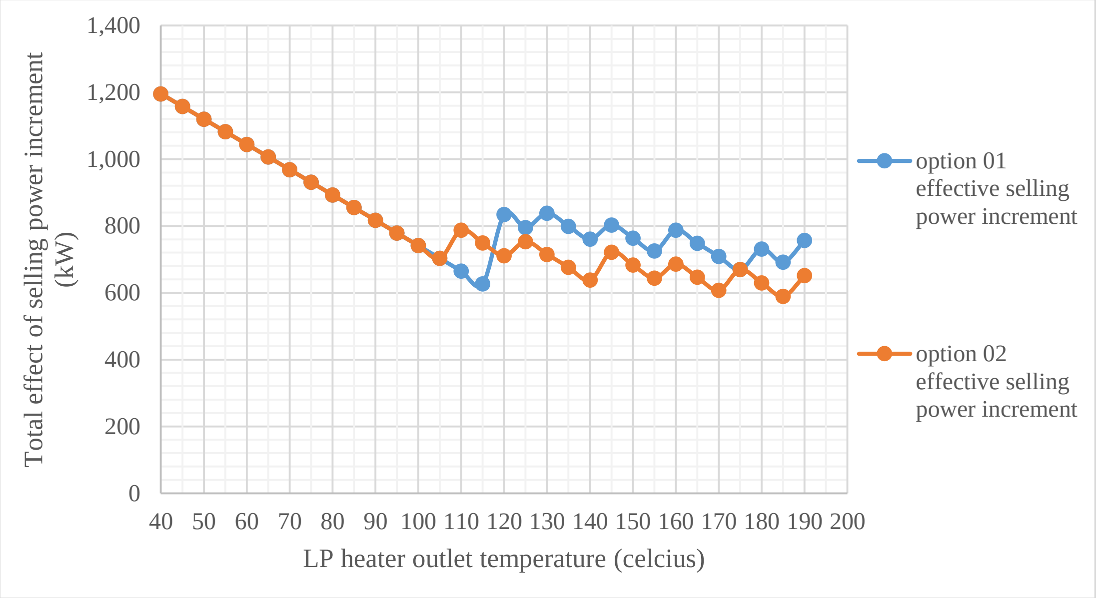


Figure 4.20: Total increment of selling power in combined systems

According to the Figure 4.20, increment of total power selling capability is high in LP heaters than the single stage or two stage vapour absorption chillers when considered individually. In addition to that, amount of energy selling increment of LP heaters are linearly varying with LP heater outlet waste heat fluid temperature.

In addition to that, heat exchangers are influenced to increase total selling power by 1,200 kW and two stage and single stage chillers with or without presence in heat exchangers are influenced for 850-600 kW and 800-600 kW respectively.

Total annual income variation based on increased selling power were summarized in Figure 4.21.

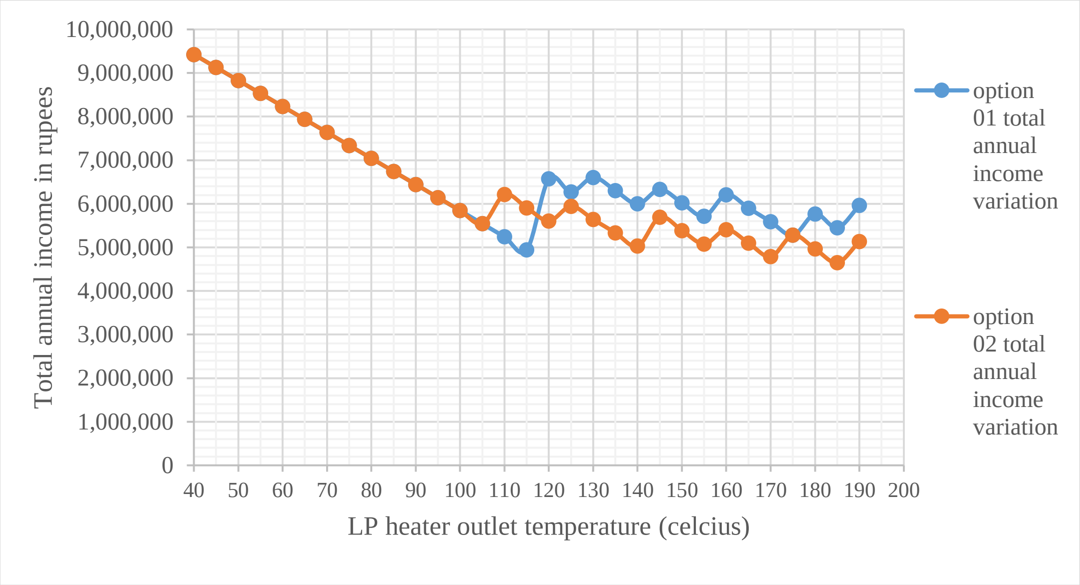


Figure 4.21: Total annual income based on increment of selling power

Total annual income was highest at 40 ^{0}C of LP heater outlet temperature and it was more than 9 million rupees. When consider the effect of combined systems, annual income was in between 5 million and 7 million in option 01 combination. Annual income was varying between 4.5 million and 6.5 million rupees.

Results of economic feasibility study was summarized in Figure 4.22 and Figure 4.23 with NPV details and IRR values at different LP heater outlet temperature at standard CBD mass flow rate for both systems.

According to the Figure 4.22, NPV is positive in between 50 ^{0}C - 175 ^{0}C of LP heater outlet temperature for option 01 combination and it is economically feasible for that range. However, option 02 system was economically feasible at more than 50 ^{0}C of LP heater outlet temperature. NPV variation was maximum around 30 million rupees in both cases based on 20 years of period.

According to the Figure 4.23, IRR variation is varied between 7% - 30% for option 01 combination and 10% - 28% for option 02 combination with LP heater outlet temperature.

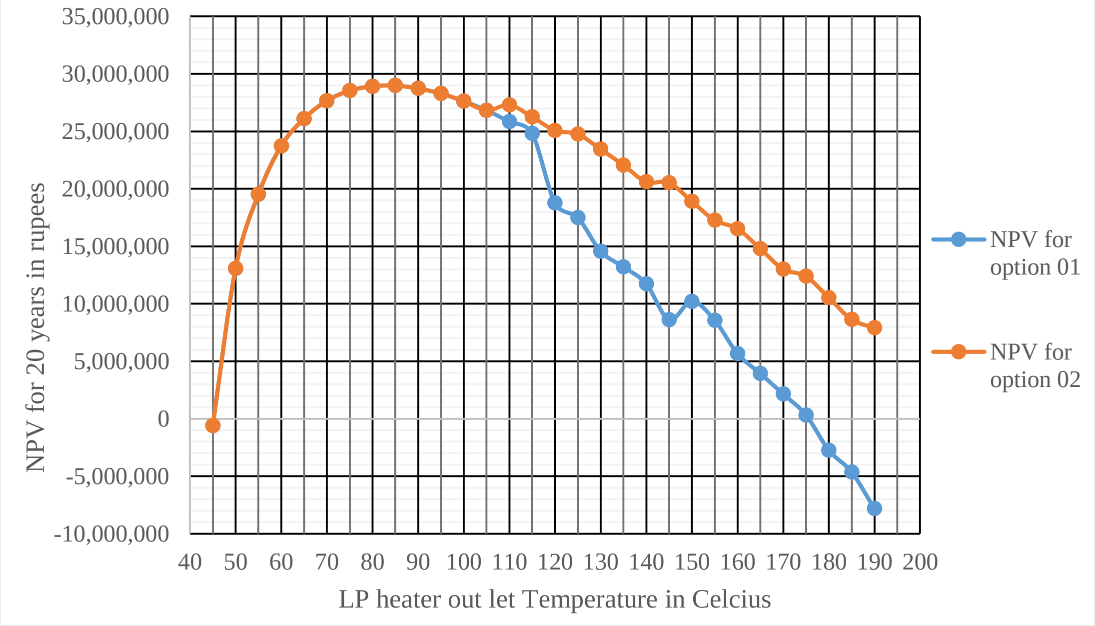


Figure 4.22: NPV variation based on expenses and incomes

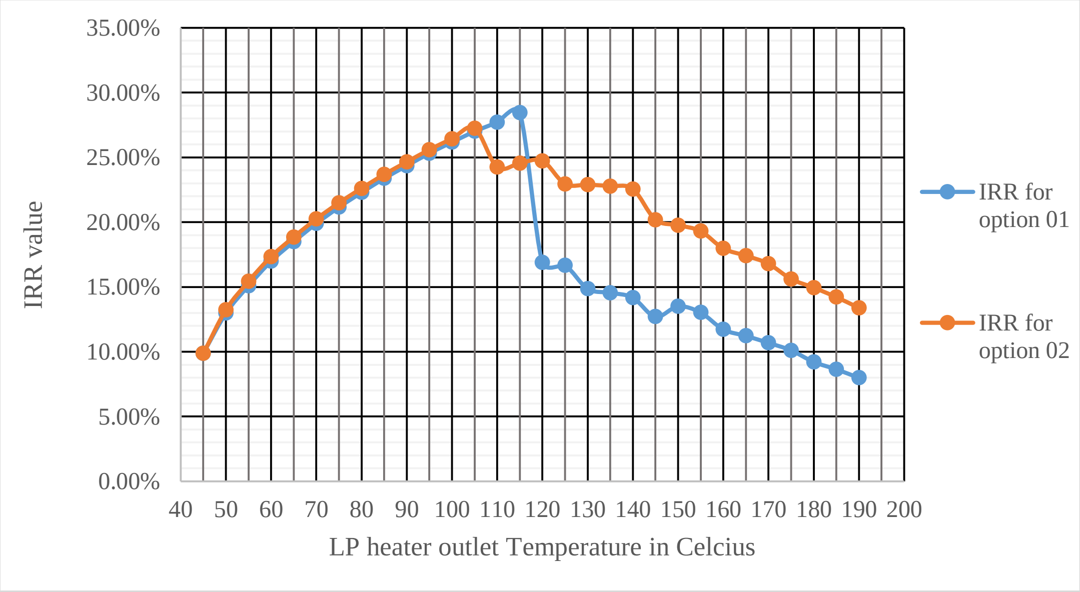


Figure 4.23: Project IRR variation with LP heater outlet temperature

5 CONCLUSION AND FUTURE WORK

An analysis of potential waste heat availability, recovery options, methods, capital cost and energy extraction per unit capital cost from boiler continuous blowdown system in Lakvijaya coal power station was carried out in this study. In addition to analysis, mathematical models have introduced to find heat exchanger grass root cost for various heat transfer area and to find energy extraction per unit capital cost for similar applications.

Even though manufacturer has recommended to carry out boiler CBD at 1% BMCR load, boiler CBD have to be increased more than recommended rates due to water quality requirements. Therefore, total waste heat availability calculated for range of CBD mass flow rate from 1% BMCR to 3% BMCR of all three boilers in the power station and result has varied from 3,950 kW to 11,851 kW.

Identified two possible opportunities to recover available waste heat through heat exchanger to heat condensate water pre heating and vapour absorption chiller plant which can be fully or partially replace electrically driven vapour compression chiller system in power plant air conditioning system. New layout was introduced for boiler CBD system with new parts and components which is containing LP heater and absorption chiller in series orientation. Single stage and two stage vapour absorption chillers were considered due to availability of heat source which was at liquid state. CBD flash tank outlet water which was at 1.4 MPa, 198 ^{0}C thermal conditions, directly sent to LP heater and then LP heater discharged waste heat fluid was sent to vapour absorption chiller. LP heater outlet temperature and boiler CBD flow rate were main independent variables.

CAPCOST ver2 software which was used to calculate the LP heaters grass root cost had limitations and given cost values for heat transfer area of 10 m^2 to 100 m^2. Due to requirement of capital cost data up to 280 m^2 of heat transfer area, regression model was developed and then predicted grass root cost values accordingly. R-

Square and Standard deviation of the developed model are 100% and 121.271 respectively and observed that this model fitted well with data set.

Energy of waste heat fluid is significant enough to increased condensate water temperature from 40.0 ^{0}C to 43.9 ^{0}C throughout all variations and that temperature increment was influenced to increased energy extraction from 107 kW to 9145 kW by all three LP heaters. Moreover, these variations are influenced to increase absorption chiller cooling load from 0 kW to 5230 kW in option 01 combination and 0 kW to 4650 kW in option 02 combinations respectively. Energy extraction of combined system was maximized at both combinations where chillers are insignificant and point is at waste heat fluid discharge temperature of 45 ^{0}C. Total energy extraction was running through minimum point because of combined effect of the system and decreasing the influence from absorption chillers. Energy extraction by chillers was low compared to LP heaters because single effect absorption machines are running in low COP range.

Total capital cost of the combined systems was varied from 100,000 US$ - 1,800,000 US$ throughout all variation and optimized total capital cost of energy extraction per unit capital cost was varied from 100,000 US$ - 400,000 US$. In optimum points, energy extraction per unit capital cost has varied from 12 – 17 kW/US$1000 even though, total variation lies in between 5 – 17 kW/US$1000 in all variation in accounted parameters.

Results show that energy extraction per unit capital cost has optimized at heat exchanger outlet temperature in between 120 ^{0}C to 95 ^{0}C, where affect from absorption chiller was insignificant and result was similar in both single stage and two stage chiller machines. Two regression models were developed for energy extraction for unit capital cost with four variables with significant accuracy of R-Sq values of 86.66% and 76.86% for two stage chiller and single stage chiller systems respectively. This model can be used to find optimal points in similar applications.

Financial analysis of combined systems at standard CBD rate was carried out based on thermodynamic and economic analysis and observed that there are many combination of system have IRR above 25% and positive NPV for 20 years.

However, all calculations are based on maximum continuous operation conditions and partial load condition based analysis can be considered as future works of research.

6 BIBLIOGRAPHY

American Coal Foundation. (n.d.). Ancient Gift Serving Modern Man. *Coal*.

B.Chandra sekhar, D.Krishnaiah, F.Anand Raju . (2014). Thermal Analysis of Multi Tube Pass Shell and Tube Heat Exchanger, . *International Journal of Innovative Research in Science, Engineering and Technology, Vol. 3*.

Chetan Undhad, P. P. (2015). Exergy Analysis On Shell & Tube Type Heat Exchanger. *International Journal of Modern Trends in Engineering and Research*, 69-73.

Du Hongda, Jing Xinliu, Li Dongfeng. (2012). *Centralized Control Operation Regulation, Revision 04.* China National Machinery & Equipment Import & Export Corporation (CMEC).

International Energy Agency. (2012). *Technology Roadmap: High-Efficiency, Low-Emissions Coal-Fired Power Generation.* International Energy Agency.

International Energy Agency Coal Industry Advisory Board. (2013). 21st Century Coal. *Advanced Technology and Global Energy Solution*.

J.B. Kitto, S.C. Stultz. (2005). *Steam its generation and use, 41st edition, Vol 1.* Ohio, U.S.A: The Babcock & Wilcox Company.

K.Burnard, S.Bhattacharya. (2011). Power generation From Coal: Ongoing Developments and Outlook. *journal of International Energy Agency*.

Keerthi R Lekshmi, Vandana S Pillai. (2015). Boiler Blowdown Analysis in an Industrial Boiler. *IOSR Journal of Engineering (IOSRJEN) Vol. 05*.

Lako, P. (2004). *Coal-Fired Power Technologies: Coal-Fired Power Options on the Brink of Climate Policies.*

Michael J. Moran, Howard N. Shapiro. (2006). *Fundamentals of Engineering Thermodynamics, 5th edition.* Chichester,England: John Wiley & Sons Ltd.

Milind V. Rane, Madhukar S. Tandale. (2005). Water-to-water heat transfer in tube-tube heat exchanger. *Applied Thermal Engineering ,Volume 25*.

N.Otter. (2002). Advanced Power Generation Technology Forum. *An Industrial Perspective on Energy RD and D.* London: N.Otter.

Vattenfall. (n.d.). Coal power.

World Coal Association. (n.d.). A Comprehensive Overview of Coal. *The Coal Resource*.

World Coal Association. (n.d.). Energy for Sustainable Development. *Coal*.