Optimization in Steam Production from Waste Heat Recovery Boiler

By

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Certificate

This is to certify that work on this thesis has been carried out by **Mariam Javed Malik, Hassan Mujtaba and Sohaib Ahmed** and completed under supervision of **Dr. Zaib Jahan** and **Lecturer Ayesha Raza** in School of Chemical and Materials Engineering (SCME), National University of Sciences and Technology, H-12, Islamabad, Pakistan.

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Submitted through

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Dedication

Our work is dedicated to our parents and families,

for their constant support and encouragement.

Acknowledgements

We would like to acknowledge and thank the dedicated faculty at our School of Chemical and Materials Engineering. This project would not have been possible without their guidance. To mention in specific, Dr Zaib Jahan and Lecturer Ayesha Raza, who served as a source of extreme guidance and encouragement for the entirety of our project.

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We are extremely indebted to our parents for believing in us and for helping us in achieving our dreams.

Abstract

Our project aims to optimize steam production from Waste Heat Recovery Boiler (WHRB) by installing a condensing economizer to ensure energy recovery and cost savings. Condensing Economizer helps to reduce the stack temperature of flue gases and the steam demand of deaerator. The project is divided into five steps. Make up water and Condensate return goes to the deaerator for stripping of dissolved gases. The deaerated Boiler Feed Water goes to the Feed Water Economizer where it is heated by heat exchange with the flue gas outlet of the WHRB. The preheated water goes to the boiler where it exchanges heat with the flue gases coming from the plant. The Boiler generates steam for the process. The condensing economizer is installed to lower the stack temperature of flue gases and pre-heat the make-up water, reducing the energy demands of the Deaerator.

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1 Introduction

The Waste Heat Recovery Boiler generates 4 tons/hr steam at a pressure 15 bar. A part of the steam generated goes to the deaerator and the other part goes to the process plant for heating purposes. The Steam produced is Saturated Steam. This steam is being generated by the heat exchange between the water (make up plus condensate returns) and the flue gas coming from the plant. One boiler operates on the flue gas of Natural gas while the other on the flue gas of Heavy Fuel Oil.

2 Literature Review

2.1 Waste Heat Recovery Boiler

2.1.1 Introduction:

The role of WHRBs in the industry economy has been profound. Plants, refineries, chemical plants and electric utilities, all have a steam plant. Steam is the most common fluid for industrial processing, heating, chilling and power generation applications. It is used as a heating source for many process heating heat exchangers, reactors, reboilers and heat transfer equipment etc. Conservation of energy is the primary focus of all the industrial advancements and WHRBs are widely used to recover as much heat content from the flue gases as possible to reduce the steam demand which in return reduces the operational costs and to reduce the adverse effects humans are causing to the environment.

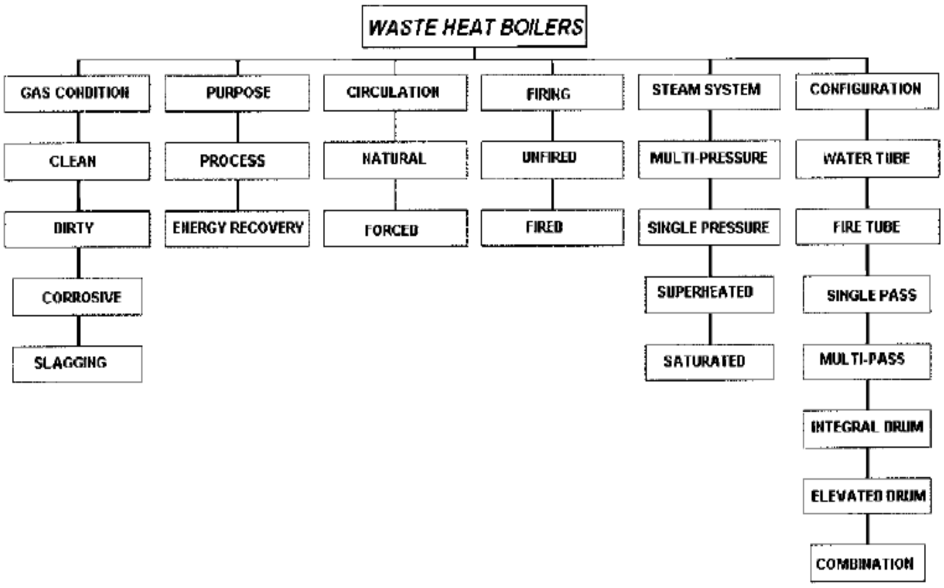


FIGURE 2.1 Classification of waste heat boilers.

These WHRBs are classified in several ways as seen in Fig. 2.1, according to the application, the type of boiler used, whether the flue gas is used for process or mainly for energy recovery, cleanliness of the gas, and boiler configuration, to mention a few. The main classification is based on whether the boiler is used for process or energy recovery.

2.1.2 Classification On The Basis Of Configuration:

Water Tube versus Fire Tube

A common classification is based on if the gas flows inside or outside the tubes. In water tube boilers, the gas flows outside the tubes and as the name suggests, water flows in the tube. While in fire tube boilers, water is in the shell and the heating medium flows in the tubes hence the name fire tube.

TABLE 2.1 A Comparison of Fire Tube and Water Tube Boilers

Variable	Fire tube boiler	Water tube boiler
Gas flow	Small—less than 50,000 lb/h	50,000 to millions of lb/h
Gas inlet temperature	Low to adiabatic combustion	Low to adiabatic combustion
Gas pressure	High—even as high as 2000 psig	Generally less than 2 psig
Firing	Possible	Possible
Type of heating surface	Bare tube	Bare and finned tubes
Superheater location	At inlet or exit of boiler	Anywhere in the gas path using screen section
Water inventory	High	Low
Heat flux-steam side	Generally low	Can be high with finned tubes
Multiple steam pressure	No	Yes
Soot blower location	Inlet or exit of boiler	Anywhere inside boiler surfaces
Multiple modules	No	Yes

The boiler at Engro Foods is Water tube that handles larger flow as compared to Fire tube boiler.

2.1.3 Classification On The Basis Of Circulation:

WHRBs as seen in Fig.2.1 can be classified according to the type of circulation system used. There are three types of systems. Natural, Forced or Once-Through.

Natural Circulation:

The system with natural circulation has vertical tubes and horizontal gas flow orientation. These units employ the difference in density between water and steam to drive the steam water mixture through the tubes and risers and back to steam drum. The phenomenon is called thermos-syphoning.

Forced Circulation:

Forced Circulation units have an opposite set up where the tubes are horizontal and the gas flow is in vertical direction. A pump is used to drive the steam-water mixture through the tubes. Steam separates from the mixture and goes to the steam header.

Once Through System:

There is no circulation in a once through system. Water enters at one end and leaves as steam at the other end of the bundle.

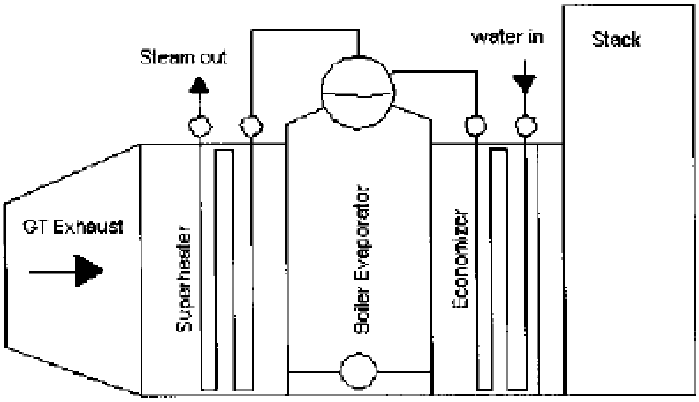


Figure 2.2 (a) Natural Circulation Unit

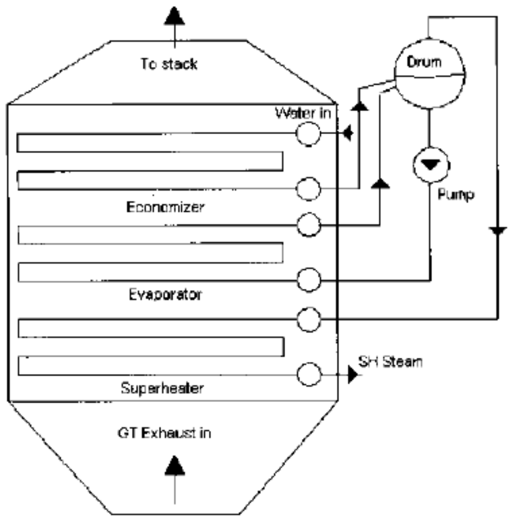


Figure 2.2 (b) Forced Circulation Unit

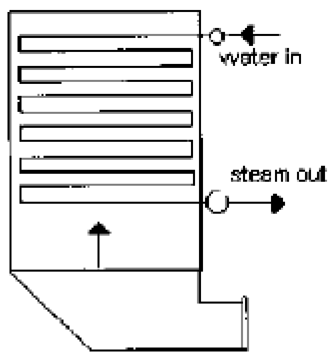


Figure 2.2 (c) Once through Unit

Our project focuses on a natural circulation unit.

2.2 Natural Gas versus Heavy Fuel Oil:

Our project aims to compare the impact of flue gases of two different fuels on the throughput of our boiler. The two fuels are Natural Gas and HFO. We take four factors into account while we perform the economic and environmental analysis of flue gas. These four factors are:

Fuel Cost: It includes the Price/unit of fuel as well as the cost of running auxiliary equipment.

- Emissions: The nature of the flue gas, whether it is polluting or clean.
- Operation and Maintenance: The byproducts that foul the boiler
- Capacity: The efficiency of the flue gas.

Natural gas is a clean and nonpolluting gas with better environmental benefits than any other fuel. It can meet the required goal at lower supply volumes and is more efficient for the same Temperature difference. The only problem associated with Natural gas is the outrages the gas supply line may suffer due to political strikes.

HFO on the other hand is the result of distillation of heavy crude oil. It is a viscous liquid fraction with a high percentage of Sulphur in it. It is a cheap fuel as compared to other liquid fuels but in comparison with natural gas, HFO has emission problems and costly stack. It can face corrosion issues at the exhaust because Sulphur oxides may react with water to form sulphuric acid.

Fuel (Mass = 100 kg/s)									
Components	**C**		**H**	**S**	**O2**	**N2**			**Total**
Component (wt%)	84.00		12.00	4.00	-	-			**100.00**
Component Flow (kg/s)	84.00		12.00	4.00	-	-			**100.00**
Moles Present (kmol/s)	7.00		12.00	0.13	-	-			**19.13**
Combustion Calculation									
	C		**H**	**S**	**O2**	**N2**			**Total**
Moles of O2 Required (kmol/s)	7.00		3.00	0.13	-	-			**10.13**
Moles of O2 Required [15% Excess] (kmol/s)	8.05		3.45	0.14	-	-			**11.64**
Moles of Air Required (kmol/s)	38.32		16.42	0.68	-	-			**55.42**
	CO2	**CO**	**H2O**	**SO2**	**O2**	**N2**	**Unburnt Fuel**		**Total**
Moles of Flue Gas (kmol/s)	3.50	0.01	4.20	0.06	1.42	43.62	13.41		**66.23**
Mass of Flue Gas (kg/s)	154.00	0.28	75.60	4.00	45.49	1,221.46	831.57		**2,332.40**
							C	**H**	
Composition of flue gas (wt%)	6.60	0.01	3.24	0.17	1.95	52.37	31.29	4.36	**100.00**
Composition of 16 kg/s flue gas	1.06	0.00	0.52	0.03	0.31	8.38	5.01	0.70	**16.00**

Table 2.2 HFO Combustion Calculations and Composition

Natural Gas (Mass = 100 kg/s)									
Components	**C**		**H**	**S**	**O2**	**N2**			**Total**
Component (wt%)	74.00		25.00	-	1.00	-			**100.00**
Component Flow (kg/s)	74.00		25.00	-	1.00	-			**100.00**
Moles Present (kmol/s)	6.17		25.00	-	0.03	-			**31.20**
Combustion Calculation									
	C		**H**	**S**	**O2**	**N2**			**Total**
Moles of O2 Required (kmol/s)	6.17		6.25	-	-	-			**12.42**
Moles of O2 Required [15% Excess] (kmol/s)	7.09		7.19	-	-	-			**14.28**
Moles of Air Required (kmol/s)	33.76		34.21	-	-	-			**67.97**
	CO2	**CO**	**H2O**	**SO2**	**O2**	**N2**	**Unburnt Fuel**		**Total**
Moles of Flue Gas (kmol/s)	3.08	0.01	8.75	-	1.72	53.50	16.77		**83.83**
Mass of Flue Gas (kg/s)	135.67	0.28	157.50	-	54.96	1,498.06	268.24		**2,114.70**
							C	**H**	
Composition of flue gas (wt%)	5.82	0.01	6.75	-	2.36	64.23	17.96	2.87	**100.00**
Composition of 15 kg/s flue gas	0.87	0.00	1.01	-	0.35	9.63	2.69	0.43	**15.00**

Table 2.3 Natural Gas Combustion Calculations and Composition

The deaerated Boiler Feed Water goes to the Feed Water Economizer where it is heated by heat exchange with the flue gas outlet of the WHRB. The preheated water goes to the boiler where it exchanges heat with the flue gases coming from the plant.

The Boiler generates steam for the process. Condensing economizer is installed to lower the stack temperature of flue gases and pre-heat the makeup water, reducing the energy demands of the Deaerator.

3 Process Description

3.1 Process Flow Diagram

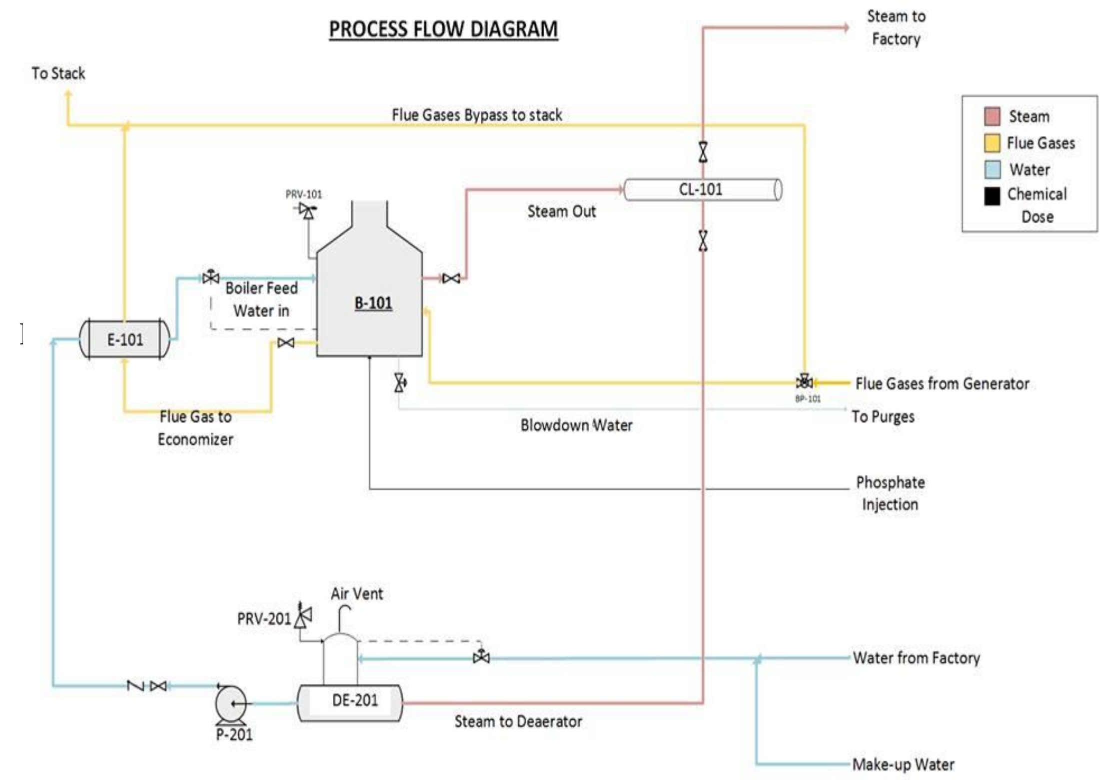
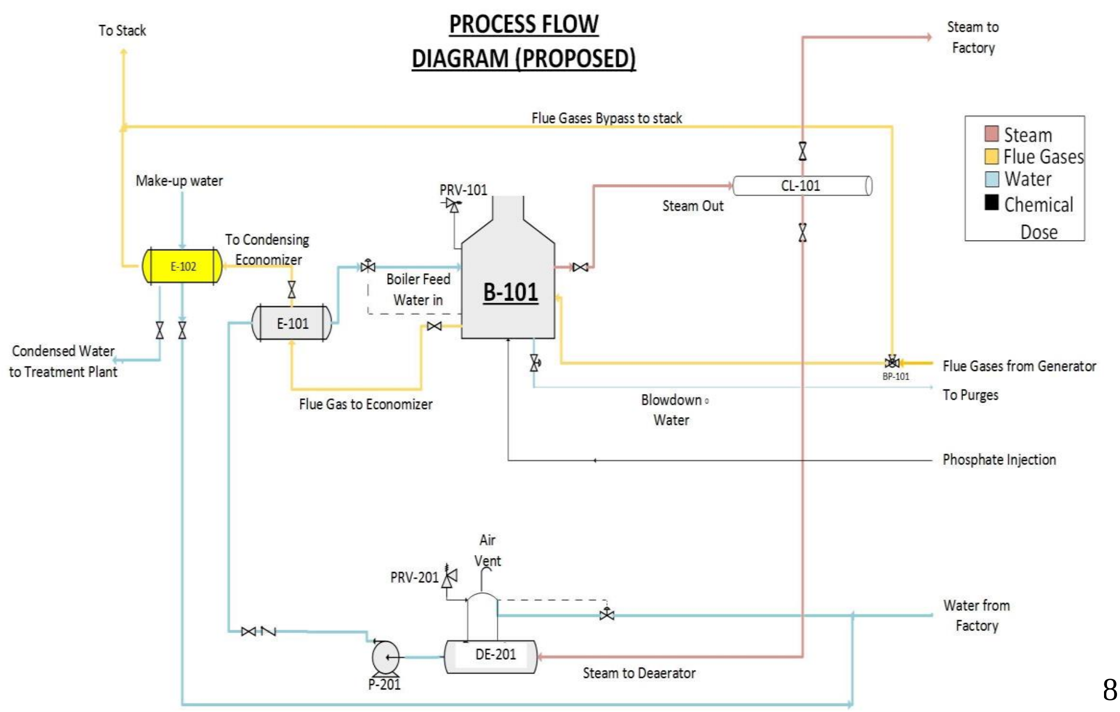


Figure 3.1a Process Flow Diagram (Existing)



3.2 Deaerator:

The cycle starts with fresh make up water and condensate returns entering the deaerator. This feed water is deaerated by the action of the steam and the oxygen and other dissolved gases get released in the vent. The deaerator works on the principle of Henry's Law which states the solubility of any gas in liquid is directly proportional to the partial pressure of gas on liquid surface. The steam injected increases the temperature and lowers the solubility of dissolved gases which are then stripped off and released in the vent along with the part of the steam. Oxygen removal is crucial because it can cause localized increase in corrosion rate on metal piping and in boiler.

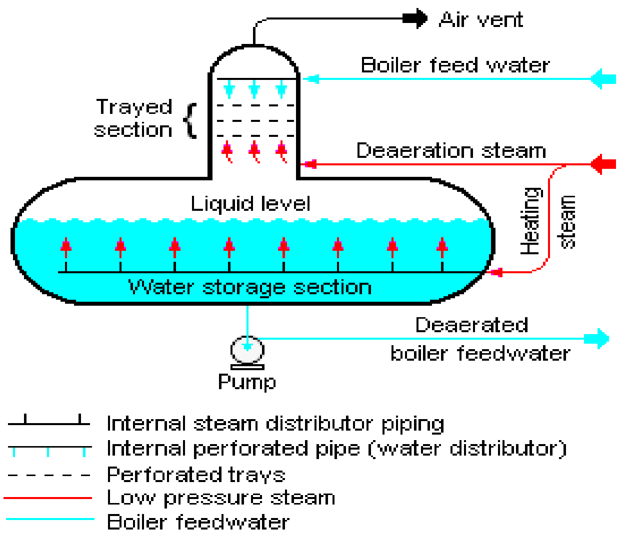


Figure 3.2 Deaerator

Steam is used for deaerating because steam is readily available and it reduces the solubility of gases in the liquid. Moreover, most of the steam used to scrub water is condensed and becomes a part of the deaerated water.

3.3 Feed Water Economizer:

As the name suggests, Feed Water Economizer is a device fitted in a boiler to save energy. Feed Water Economizer is an essentially a shell and tube heat exchanger. It is a water tube heat exchanger in which the Deaerated Boiler Feed Water flows in the tube while the flue gas outlet of the boiler flows in the shell. Feed Water economizer preheats the water before sending it to the boiler reducing the energy demands of the boiler and at the same time, reducing the stack temperature of flue gases while avoiding the low temperature corrosion

3.4 Boiler:

A boiler as the name suggests is used to boil water to turn it into steam. Boiler is a necessity in every industry as steam is widely used for various purposes. At Engro Foods, the steam produced from the boiler is saturated steam at 15 bars. This steam goes to the steam header where a part of it goes to the deaerator and the rest goes to the plant for the heating purposes.

Steam is generated by utilizing the heat content of the flue gas coming from the plant. Instead of sending this flue gas directly to stack, WHRB utilizes its heat content to generate steam. Since the boiler uses waste heat as a heating medium, the capacity of WHRB at Engro Foods is 10 Mt/hr. currently the boiler is generating steam at 4 Mt/hr.

3.5 Condensing Economizer:

Condensing economizer further increases the efficiency of the boiler and recycles water in the flue gas since water is a precious commodity in a lot of places. This heat exchanger recovers both heat of condensation and sensible heat from flue gases. Here, the stack temperature is further lowered resulting in the low temperature corrosion. Since the water produced is acidic and the formation of sulphuric acid in case of HFO flue gas, the material of construction for Condensing Economizer is SS 904L. **Grade *904L stainless steel* is fully austenitic *stainless steel* with low carbon content. This high alloy *stainless steel* is added with copper to improve its resistance to strong reducing acids, such as sulphuric acid.**

The makeup water instead of going directly to the deaerator goes to the condensing economizer first where it is preheated and then sent to the deaerator. This preheated feed water reduces the steam demand of the deaerator by 36%.

4 Material Balance

4.1 Deaerator:

Steam in calculation:

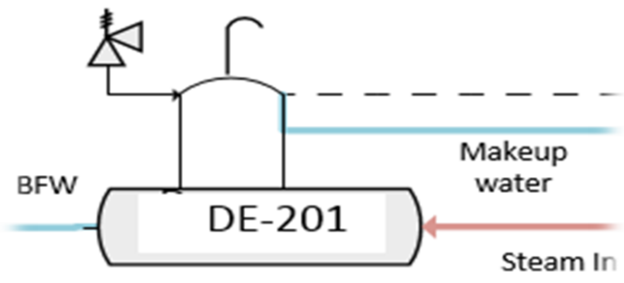


Figure 4.1Deaerator

$$m_w H_w + m_s H_s = (m_s + m_w) H_o$$

$$m_s = \frac{m_w (H_o - H_w)}{(H_s - H_o)}$$

DEAERATOR MASS BALANCE	
Streams	
M_W = mass of inlet water (kg/hr)	4000
H_W = Enthalpy of Inlet water (KJ/kg)	251.56
H_S = Enthalpy of Steam at the given Temperature	2793.2
H_O = Enthalpy of the outlet water at specified temperature	461.63
Mass flow of steam added	360.39
M_V = Mass flowrate of Vent = (1 percent of Steam added)	3.604

Table 4.1 (a) Deaerator Balance 1 1

Known Values:

$$M_W = Mass\ of\ inlet\ water = 4000\ {}^{kg}/_{hr}$$

$$H_W = Enthalpy\ of\ inlet\ water = 251.56\ {}^{kJ}/_{kg}$$

$$H_S = Enthalpy\ of\ Steam\ at\ the\ given\ temperature = 2793.2\ {}^{kJ}/_{kg}$$

$$H_O = Enthalpy\ of\ outlet\ water\ at\ the\ specified\ temperature$$

$$= 461.63\ {}^{kJ}/_{kg}$$

Unknown Values:

$$M_S = Mass\ flow\ of\ Steam\ In$$

$$= \frac{M_W(H_O - H_W)}{(H_S - H_O)}$$

$$= \frac{4000(461.63 - 251.56)}{(2793.2 - 461.63)}$$

$$M_S = 360\ {}^{kg}/_{hr}$$

$$Mass\ Flowrate\ of\ Vent = 1\%\ of\ Steam\ Added$$

$$= 360.39 \times \frac{1}{100}$$

$$= 3.604\ {}^{kg}/_{hr}$$

Overall Material Balance on Deaerator:

Inlet		**Outlet**	
Stream	Flowrate kg/hr	Stream	Flowrate kg/hr
Inlet water	4000	Boiler Feed water	4356.79
Steam	360.39	Vent(1% of Steam added)	3.6039

Table 4.1 (b) Deaerator Balance Summary 1

4.2 Waste Heat Recovery Boiler:

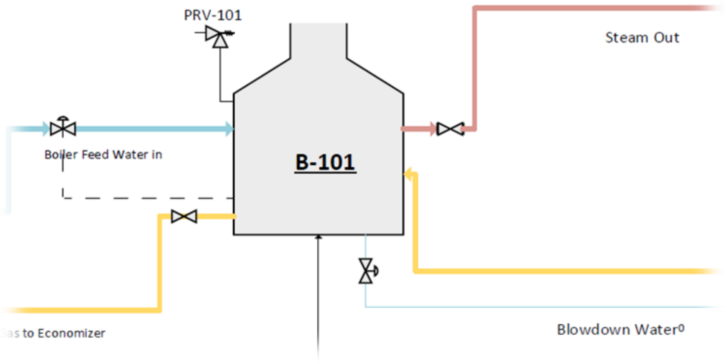


Figure 4.2 WHRB

Material Balance on Boiler			
Inlet		**Outlet**	
Stream	Flowrate (kg/hr)	**Stream**	Flowrate (kg/hr)
Boiler Feed Water	4356.78843	**Blowdown**	356.87173
Chemical water	0.0833	**Steam Generated**	4000
4356.87173		**4356.87173**	

Table 4.2 (a) WHRB Balance 1

Known Values:

$$\boldsymbol{Boiler\ Feed\ Water = 4356.79\ \frac{tons}{day}}$$

$$\boldsymbol{Chemical\ Water = 0.0833\ \frac{tons}{day}}$$

$$\boldsymbol{Steam\ Generated = 4000\ \frac{tons}{day}}$$

Unknown Values:

$$\boldsymbol{Blowdown = BFW + Chemical\ Water - Steam\ Generated}$$

$$\boldsymbol{= 4356.79 + 0.0833 - 4000}$$

$$\boldsymbol{= 356.87\ \frac{tons}{day}}$$

TDS Balance:

TDS BALANCE			
Inlet		**Outlet**	
Boiler Water (kg/hr)	4357	**Blowdown (kg/hr)**	356.9
TDS ppm	50	**TDS**	610.4

Table 4.2 (b) TDS Balance 1

Known Values:

$$\boldsymbol{Boiler\ Water = 4357\ \frac{kg}{hr}}$$

$$\boldsymbol{TDS\ in\ BFW\ = 50\ ppm}$$

$$\boldsymbol{Blowdown = 356.9\ \frac{kg}{hr}}$$

Unknown Values:

$$\boldsymbol{TDS\ in\ Blowdown = \frac{Boiler\ Water\ \times TDS_{IN}}{Blowdown}}$$

$$\boldsymbol{= \frac{4357 \times 50}{356.9} = 610.4\ ppm}$$

4.3 Boiler Economizer:

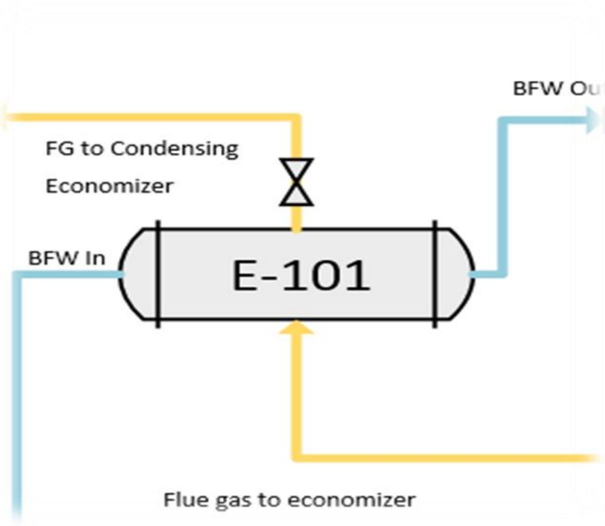


Fig 4.3 Feed Water Economizer

Material Balance on Economizer for Natural Gas			
Inlet		**Outlet**	
Stream	Flowrate(kg/hr)	**Stream**	Flowrate (kg/hr)
Boiler Feed Water	4356.78843	**Boiler Feed water out**	4356.78843
Flue gas in	54000	**Flue gas out**	54000
58356.78843		**58356.78843**	

Table 4.3 (a) Natural Gas Economizer

Material Balance on Economizer for HFO			
Inlet		**Outlet**	
Stream	Flowrate(kg/hr)	**Stream**	Flowrate (kg/hr)
Boiler Feed Water	4356.78843	**Boiler Feed water out**	4356.78843
Flue gas in	57600	**Flue gas out**	57600
61956.78843		**61956.78843**	

Table 4.3 (b) HFO Economizer

4.4 Condensing Economizer:

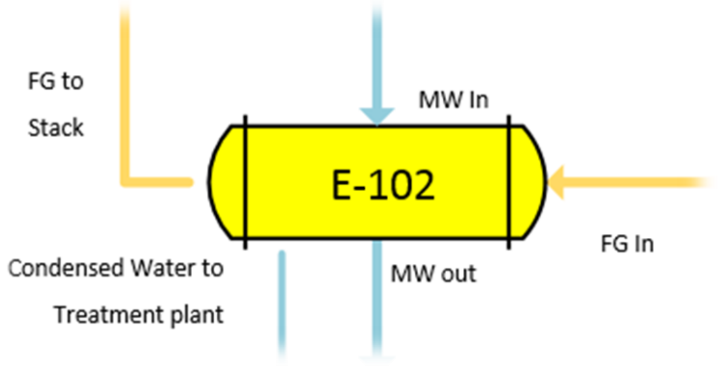


Fig 4.4 Condensing Economizer

Calculations for Natural Gas

Condensing Economizer (For Natural Gas)			
Inlet		**Outlet**	
Flue gas in (kg/hr)	54000	**Water condensed**	11.00%
Water In flue gas (weight %)	6.75%	**Water condensed (kg/hr)**	400.95
		Water left	89.00%
		Water leaving in flue gas (kg/hr)	3244.05

Table 4.4 (a) Balance for Natural Gas

Flow rate of water condensed:

Known Values:

$$\boldsymbol{Flue\ Gas\ in = 54000\frac{kg}{hr}}$$

$$\boldsymbol{Water\ in\ Flue\ Gas\ (Wt\%) = 6.75\ \%}$$

$$\boldsymbol{Water\ Condensed = 11\ \%}$$

Unknown Values:

$$\boldsymbol{Water\ Condensed}$$

$$\boldsymbol{= FG\ in \times Wt\ \%\ of\ water\ in\ FG \times Wt\ \%\ of\ water\ condensed}$$

$$\boldsymbol{= 54000 \times 0.0675 \times 0.11}$$

$$\boldsymbol{= 400.95\ \frac{kg}{hr}}$$

Flow rate of water leaving Economizer:

Known Values:

$$\boldsymbol{Flue\ Gas\ in = 54000\frac{kg}{hr}}$$

$$\boldsymbol{Water\ in\ Flue\ Gas\ (Wt\%) = 6.75\ \%}$$

$$\boldsymbol{Water\ Left = 89\ \%}$$

Unknown Values:

$$\boldsymbol{Water\ leaving\ in\ FG}$$

$$\boldsymbol{= FG\ in \times Wt\ \%\ of\ water\ in\ FG \times Wt\ \%\ of\ water\ left}$$

$$\boldsymbol{= 54000 \times 0.0675 \times 0.89}$$

$$\boldsymbol{= 3244.05\ \frac{kg}{hr}}$$

Calculation for HFO Fuel:

Condensing Economizer (For HFO)			
Total mass flowrate of SO_2 (kg/hr)	97.92	**Mass flowrate of H_2SO_4 (kg/hr)**	10.4958
Mass flowrate of SO_2 to give SO_3 (kg/hr)	6.8544	**Water to make H_2SO_4 (kg/hr)**	1.927
Moles of SO_2 to give SO_3 (kmol/hr)	0.1071	**Water condensed (kg/hr)**	205.2864
Water in flue gas (kg/hr)	1866.24	**Water out in flue gas (kg/hr)**	1659.0266

Table 4.4 (b) Balance for HFO

Calculation for flow rate of H_2SO_4

Known Values:

$$\boldsymbol{Total\ mass\ flowrate\ of\ SO_2 = 97.92\ \frac{kg}{hr}}$$

$$\boldsymbol{Mass\ of\ SO_2\ to\ give\ SO_3 = 0.1071\ \frac{kg}{hr}}$$

Unknown values:

$$\boldsymbol{Mass\ flowrate\ of\ H_2SO_4}$$
$$\boldsymbol{= mass\ flowrate\ of\ SO_2 \times Mass\ of\ SO_2\ to\ give\ SO_3}$$
$$\boldsymbol{= 97.92 \times 0.1071}$$
$$\boldsymbol{= 10.50\ \frac{kg}{hr}}$$

Calculation for flow rate of water in FG:

Known Values

$$\boldsymbol{Water\ in\ Flue\ Gas = 1866.24\ \frac{kg}{hr}}$$
$$\boldsymbol{Water\ to\ make\ H_2SO_4 = 1.927\frac{kg}{hr}}$$
$$\boldsymbol{Water\ Condensed = 205.59\ \frac{kg}{hr}}$$

Unknown Values:

$$\boldsymbol{Water\ out\ in\ Flue\ Gas}$$
$$\boldsymbol{= Water\ in\ FG - Water\ to\ make\ H_2SO_4 - water\ condensed}$$
$$\boldsymbol{= 1866.24 - 1.927 - 205.59}$$
$$\boldsymbol{= 1659.027\ \frac{kg}{hr}}$$

5 Energy Balance

5.1 Deaerator

Deaerator	
Mass flowrate of water in (kg/hr)	4000
Mass flowrate of steam in (kg/hr)	360.3
Mass flowrate of boiler feed (kg/hr)	4356.79
Enthalpy of water in (kJ/kg)	251.56
Enthalpy of steam in (kJ/kg)	2793.20
Enthalpy of boiler feed(kJ/kg)	461.63
Heat rate of water in (kJ/hr)	1.006E+06
Heat rate of steam in (kJ/hr)	1.006E+06
Heat rate of boiler feed (kJ/hr)	2.01E+06
Heat rate of vent (kJ/hr)	1.41E+03

Table 5.1 Deaerator Energy Balance

Known Values:

$$\boldsymbol{Mass\ flowrate\ of\ Water\ in = 4000\ \frac{kg}{hr}}$$

$$\boldsymbol{Enthaply\ of\ water\ in = 251.56\ \frac{kJ}{kg}}$$

Unknown Values:

$$\boldsymbol{Heat\ rate\ of\ water\ in}$$
$$\boldsymbol{= Mass\ flowrate\ of\ water\ in \times Enthalpy\ of\ water\ in}$$
$$\boldsymbol{= 4000 \times 251.56}$$
$$\boldsymbol{= 1006240\ \frac{kJ}{hr}}$$

Known Values:

$$\boldsymbol{Mass\ flowrate\ of\ steam\ in = 360.3\ \frac{kg}{hr}}$$
$$\boldsymbol{Enthalpy\ of\ steam\ in = 2793.20\ \frac{kJ}{kg}}$$

Unknown Values:

$$\boldsymbol{Heat\ rate\ of\ steam\ in}$$
$$\boldsymbol{= Mass\ flowrate\ of\ steam\ in \times Enthalpy\ of\ steam\ in}$$
$$\boldsymbol{= 360.3 \times 2793.20}$$
$$\boldsymbol{= 1006390\ \frac{kJ}{hr}}$$

Known Values:

$$\boldsymbol{Mass\ flowrate\ of\ boiler\ feed = 4356.79\ \frac{kg}{hr}}$$
$$\boldsymbol{Enthalpy\ of\ boiler\ feed = \ 461.63\ \frac{kJ}{kg}}$$

Unknown Values:

$$\boldsymbol{Heat\ rate\ of\ boiler\ feed}$$
$$\boldsymbol{= Mass\ flowrate\ of\ BFW\ in \times Enthalpy\ of\ BFW\ in}$$
$$\boldsymbol{= 4356.79 \times 461.63}$$
$$\boldsymbol{= 2011225\ \frac{kJ}{hr}}$$

Known Values:

$$\boldsymbol{Heat\ rate\ of\ water\ in = 1006240\ \frac{kJ}{hr}}$$
$$\boldsymbol{Heat\ rate\ of\ steam\ in = 1006390\ \frac{kJ}{hr}}$$
$$\boldsymbol{Heat\ rate\ of\ boiler\ feed = 2011225\ \frac{kJ}{hr}}$$

Unknown Values:

$$\boldsymbol{Heat\ rate\ of\ vent}$$
$$\boldsymbol{= (heat\ rate\ of\ water\ in + heat\ rate\ of\ steam\ in)}$$
$$\boldsymbol{- Heat\ rate\ of\ boiler}$$
$$\boldsymbol{= 1006240 + 1006390 - 2011225}$$
$$\boldsymbol{= 1410\ \frac{kJ}{hr}}$$

5.2 Boiler Feed Water Pump:

PUMP	
Mass flowrate	4356.79
Temperature (K)	383
Specific Volume (m^3/kg)	1052
Coefficient of volume expansion (1/K)	0.0015
Inlet Pressure (kPa)	500.9
Outlet Pressure (kPa)	1860
Enthalpy change (kJ/kg)	0.61
Work (kJ/hr)	3534.043

Table 5.2 Pump Energy Balance

Calculation for enthalpy change:

Known Values:

$$\boldsymbol{Temperature = 383\ K}$$

$$\boldsymbol{Specific\ Volume = 1052\frac{m^3}{kg}}$$

$$\boldsymbol{Coefficient\ of\ volume\ expansion = 0.0015}$$

$$\boldsymbol{Inlet\ Pressure = 500.9\ kPa}$$

$$\boldsymbol{Outlet\ Pressure = 1860\ kPa}$$

Unknown Values:

$$\boldsymbol{Enthalpy\ Change = \frac{Sp.Vol \times (1 - coefficeint\ of\ expansion \times Temp) \times (\Delta P)}{10^6}}$$

$$\boldsymbol{= \frac{1052 \times \left(1 - (0.0015 \times 383)\right) - (1860 - 500.9)}{10^6}}$$

$$\boldsymbol{= 0.61\ \frac{kJ}{kg}}$$

Calculation for Work Done by Pump:

Known Values:

$$Mass\ Flowrate\ of\ BFW = 4356.79\ \frac{kg}{hr}$$

$$Enthalpy\ Change = 0.61\ \frac{kJ}{kg}$$

$$Efficiency = 75\%$$

Unknown values:

$$Pump\ Work = \frac{(Mass\ flowrate\ of\ BFW \times Enthalpy\ Change)}{Efficiency}$$

$$= \frac{4356.79 \times 0.61}{0.75}$$

$$= 3534.043\ \frac{kJ}{hr}$$

5.3 Boiler Economizer

	Natural Gas
Water Temp in, °C	112
Water Temp out, °C	165
Flue gas in, °C	210
Flue gas out, °C	184.57
Enthalpy of water in, (kJ/kg)	462.62
mass flowrate of water, (kg/hr)	4356.79
Enthalpy of water out, (kJ/kg)	697.94
Flue gas flow(kg/hr)	54000
Sp. Heat of flue gas (kJ / kg K)	1.10
Q absorbed by water (kJ/hr)	1.03E+06
Delta T for flue gas (°C)	25.43

Table 5.3 (a) FW Economizer Energy Balance for Natural Gas

For Natural Gas Fuel:

Calculation for Heat Absorbed by BFW:

Known Values:

$$\boldsymbol{Enthalpy\ of\ Water\ out = 697.94\ \frac{kJ}{kg}}$$

$$\boldsymbol{Enthalpy\ of\ water\ in = 462.62\ \frac{kJ}{kg}}$$

$$\boldsymbol{Mass\ flowrate\ of\ water = 4356.79\ \frac{kg}{hr}}$$

Unknown Values

$$\boldsymbol{Heat\ Absorbed\ by\ water}$$
$$\boldsymbol{= Mass\ flowrate\ of\ water\ in \times Change\ in\ enthalpy}$$
$$\boldsymbol{= (4356.79 \times (697.94 - 462.62)}$$
$$\boldsymbol{= 1025240\ \frac{kJ}{hr}}$$

Calculation for Change in Temperature of Flue Gas:

Known Values:

$$\boldsymbol{Q\ absorbed\ by\ water = 1025240\ \frac{kJ}{hr}}$$

$$\boldsymbol{Sp.Heat\ of\ flue\ gas = 1.10\ \frac{kJ}{kgK}}$$

$$\boldsymbol{Flowrate\ of\ flue\ gas = 54000\ \frac{kg}{hr}}$$

$$\boldsymbol{Flue\ gas\ density = 0.68}\frac{\boldsymbol{kg}}{m^3}$$

Unknown Values:

$$\boldsymbol{Change\ in\ Temp\ of\ FG = \frac{(Heat\ absorbed\ by\ water)}{(FG\ flowrate \times FG\ Sp.Heat)}}$$
$$= \frac{\boldsymbol{1025240}}{\boldsymbol{(0.68 \times 1.10 \times 54000)}}$$
$$\boldsymbol{= 25.43}\ ℃$$

For HFO Fuel:

	HFO
Water Temp in, °C	112
Water Temp out, °C	165
Flue gas in, °C	205
Flue gas out, °C	188.05
Enthalpy of water in, (kJ/kg)	462.62
mass flowrate of water, (kg/hr)	4356.79
Enthalpy of water out, (kJ/kg)	697.94
Flue gas flow(kg/hr)	57600
Flue gas density	0.98
Sp. Heat of flue gas (kJ / kg K)	1.07
Q absorbed by water (kJ/hr)	1.03E+06
Delta T for flue gas °C	16.95

Table 5.3 FW Economizer Energy Balance for HFO

Calculation for Heat Absorbed by BFW:

Known Values:

$$\boldsymbol{Enthalpy\ of\ water\ out = 697.94\ \frac{kJ}{kg}}$$

$$\boldsymbol{Enthalpy\ of\ water\ in = 462.62\frac{kJ}{kg}}$$

$$\boldsymbol{Mass\ flowrate\ of\ water = 4356.79\ \frac{kg}{hr}}$$

Unknown Values

$$\boldsymbol{Heat\ Absorbed\ by\ water}$$
$$\boldsymbol{= Mass\ flowrate\ of\ water\ in \times Change\ in\ enthalpy}$$
$$\boldsymbol{= (4356.79 \times (697.94 - 462.62)}$$
$$\boldsymbol{= 1025240\ \frac{kJ}{hr}}$$

Calculation for Change in Temperature of Flue Gas:

Known Values:

$$\boldsymbol{Q\ absorbed\ by\ water = 1025240\ \frac{kJ}{hr}}$$

$$\boldsymbol{Sp.Heat\ of\ flue\ gas = 1.07\ \frac{kJ}{kgK}}$$

$$\boldsymbol{Flowrate\ of\ flue\ gas = 57600\ \frac{kg}{hr}}$$

$$\boldsymbol{Flue\ gas\ density = 0.98\frac{kg}{m^3}}$$

Unknown Values:

$$\boldsymbol{Change\ in\ Temp\ of\ FG = \frac{(Heat\ absorbed\ by\ water)}{(FG\ flowrate \times FG\ density \times FG\ Sp.Heat)}}$$

$$= \frac{\mathbf{1025240}}{(\mathbf{0.98 \times 1.07 \times 57600})}$$

$$= \mathbf{19.95}\ ℃$$

5.4 Waste Heat Recovery Boiler

	NG Fuel
Steam Temp. °C	201.924
Steam Pressure kPa	15.1685
Steam Flow (kg/hr)	4000
Boiler Feed water Temp. °C	165
Boiler Feed water press. kPa	17.5
Enthalpy of Steam (kJ/kg)	2793
Enthalpy of Feed water (kJ/g)	697.942
Flue gas flow(kg/hr)	54000
flue gas density (kg/m^3)	0.68
Sp. Heat of flue gas	1.15
Flue gas inlet temp. °C	450
Flue gas outlet temp. °C	210
Total heat input in boiler(kJ/hr)	10134720
Total heat out from boiler (KJ/hr)	8381032
Boiler efficiency (%)	83

Table 5.4 (a) WHRB Energy Balance for Natural Gas

For Natural Gas Fuel:

Calculation for Total Heat Input in WHRB:

Known Values:

$$Flue\ gas\ flowrate = 54000\ \frac{kg}{hr}$$

$$Flue\ gas\ density = 0.68\frac{kg}{m^3}$$

$$Sp.Heat\ of\ flue\ gas = 1.15\ \frac{kJ}{kgK}$$

$$Flue\ gase\ inlet\ Temp = 450\ ℃$$

$$Flue\ gas\ out\ Temp = 210\ ℃$$

Unknown Values:

$$Total\ Heat\ Input\ in\ WHRB = (m \times cp \times \Delta T)$$

$$= 54000 \times 0.68 \times 1.15 \times (450 - 210)$$

$$= 10134720\ \frac{kJ}{hr}$$

Calculation for Total heat out from WHRB:

Known Values:

$$Enthalpy\ of\ feed\ water = 697.94\ \frac{kJ}{kg}$$

$$Enthalpy\ of\ steam = 2793\ \frac{kJ}{kg}$$

$$Steam\ flowrate = 4000\ \frac{kg}{hr}$$

Unknown Values:

$$Heat\ out\ from\ WHRB = M_S(H_s - H_{BFW})$$

$$= (2793 - 697.94) \times 4000$$

$$= 8381032\ \frac{kJ}{hr}$$

Calculation for Boiler Efficiency:

Known Values:

$$\boldsymbol{Total\ Heat\ input\ in\ boiler = 10134720\ \frac{kJ}{kg}}$$

$$\boldsymbol{Total\ Heat\ out\ from\ boiler = 83810232\ \frac{kJ}{kg}}$$

Unknown Values:

$$\boldsymbol{Boiler\ Efiiciency = \left(\frac{Heat\ out}{Heat\ in}\right) \times 100}$$

$$= \mathbf{83}\ \%$$

For HFO Fuel

	HFO Fuel
Steam Temp. °C	201.924
Steam Pressure kPa	15.1685
Steam Flow (kg/hr)	4000
Boiler Feed water Temp. °C	165
Boiler Feed water press. kPa	17.5
Enthalpy of Steam (kJ/kg)	2793
Enthalpy of Feed water (kJ/g)	697.942
Flue gas flow(kg/hr)	57600
flue gas density (kg/m^3)	0.98
Sp. Heat of flue gas	1.11
Flue gas inlet temp. °C	380
Flue gas outlet temp. °C	205
Total heat input in boiler(kJ/hr)	10965024
Total heat out from boiler (kJ/hr)	8381032
Boiler efficiency (%)	76
Losses (kJ/hr)	2583992

Table 5.4 (b) WHRB Energy Balance for HFO

Calculation for Total Heat Input in WHRB:

Known Values:

$$\boldsymbol{Flue\ gas\ flowrate = 57600\ \frac{kg}{hr}}$$

$$\boldsymbol{Flue\ gas\ density = 0.98\frac{kg}{m^3}}$$

$$\boldsymbol{Sp.Heat\ of\ flue\ gas = 1.10\ \frac{kJ}{kgK}}$$

$$\boldsymbol{Flue\ gase\ inlet\ Temp = 380}\ ℃$$

$$\boldsymbol{Flue\ gas\ out\ Temp = 205}\ ℃$$

Unknown Values:

$$\boldsymbol{Total\ Heat\ Input\ in\ WHRB}$$
$$\boldsymbol{= (FG\ flowrate \times FG\ Density \times Sp.Heat \times \Delta T)}$$
$$\boldsymbol{= 57600 \times 0.98 \times 1.1 \times (380 - 205)}$$

Calculation for Total heat out from WHRB:

Known Values:

$$\boldsymbol{Enthalpy\ of\ feed\ water = 697.94\ \frac{kJ}{kg}}$$

$$\boldsymbol{Enthalpy\ of\ steam = 2793\ \frac{kJ}{kg}}$$

$$\boldsymbol{Steam\ flowrate = 4000\ \frac{kg}{hr}}$$

Unknown Values:

$$\boldsymbol{Heat\ out\ from\ WHRB}$$
$$\boldsymbol{= Enthalpy\ of\ steam - Enthalpy\ of\ FW \times Steam\ flowrate}$$
$$\boldsymbol{= (2793 - 697.94) \times 4000}$$
$$\boldsymbol{= 8381032\ \frac{kJ}{hr}}$$

Calculation for Boiler Efficiency:

Known Values:

$$\boldsymbol{Total\ Heat\ input\ in\ boiler = 10965024\ \frac{kJ}{kg}}$$

$$\boldsymbol{Total\ Heat\ out\ from\ boiler = 8381023\ \frac{kJ}{kg}}$$

Unknown Values:

$$\textbf{Boiler Efiiciency} = \left(\frac{\textbf{Heat out}}{\textbf{Heat in}}\right) \times \mathbf{100}$$

$$= \mathbf{76}\ \%$$

6 Design and Sizing

6.1 Natural Gas as a Fuel:

6.1.1 Feed Water Economizer

Service	FW Economizer
Type	Floating Head Heat Exchanger
Fluid Allocation	Tube Side = Water
	Shell Side = Flue Gases

Tube Side Water

$T_{in} = 112\ °C$ $T_{out} = 165\ °C$ $Massflowrate = 4232.34\ \frac{kg}{hr}$

$T_{avg} = 138.5\ °C$

Shell Side Flue Gas

$T_{in} = 210\ °C$ $T_{out} = 184\ °C$ $Massflowrate = 54000\ \frac{kg}{hr}$

$T_{avg} = 197\ °C$

6.1.1.1Properties of Shell and Tube Side Fluid

Physical Properties of Water

Physical Property	Unit	Tube Side Water
Density (ρ)	kg/m^3	995.00
Specific Heat (C_P)	kJ/kg .°C	4.200
Viscosity (µ)	mNs/m^2	0.800
Thermal Conductivity (k)	W/m°C	0.59
Assumption		
No of Passes (N_P)		4
Fouling Factor (h_d) (from table 6 a)	$W/m^2.°C$	3,000

Physical Properties of Flue gas

Physical Property	Unit	Flue Gas
Density (ρ)	kg/m^3	0.68
Specific Heat (cp)	kJ/kg°C	1.090
Viscosity (μ)	mNs/m^2	0.025
Thermal Conductivity (k)	W/m°C	0.0377
Assumption		
No of Passes (N_P)		2
Fouling Factor (h_d) (from table 6 a)	$W/m^2.°C$	4,000

We assume our heat transfer coefficient $\boldsymbol{U = 110\,\frac{W}{m^2C}}$ (from table 6 b)

LMTD

$$LMTD = \frac{\Delta T2 - \Delta T1}{\ln(\frac{\Delta T2}{\Delta T1})}$$

$$\Delta T1 = 210 - 165 = 45°C$$

$$\Delta T2 = 184 - 112 = 72°C$$

$$LMTD = 57,45°C$$

Corrected LMTD

$$R = \frac{T1 - T2}{t2 - t1}$$

$$R = 0.49$$

$$S = \frac{t2 - t1}{T1 - t1}$$

$$S = 0.54$$

$$\Delta Tm = Ft\,\Delta Tlm$$

$$\Delta Tm = 49\ C$$

Where Ft is found from Figure 6 a

6.1.1.2 Heat Duty and Heat transfer Area:

$$Q = mC\Delta T$$

$$A = \frac{Q}{U\Delta Tlm}$$

	Units	Tube	Shell
Flow rate (m)	kg/h	4,232.34	54,000
Heat Duty (Q)	kW	261.70	425

$$A = 78.21m^2$$

6.1.1.3 Tube Size and Tube Layout

Material of Construction of Tube: **Carbon Steel**

$$do = 25mm$$

$$P_t = triangular\ pitch$$

$$L = 1.830\ m$$

$$BWG = 16$$

$$d_i = 16mm$$

$Heat\ Transfer\ Factor = 0.003$ *(from figure 6 b)*

Calculations

Property	*Value*	*Unit*
Tube Pitch (P_t)	31.250	mm
Area of one tube (A_1)	143.655	mm^2
No of tubes (N_t)	544	
Tube/pass	4	136.1089124
Tube cross sectional area (A_C)	200.960000	mm^2
Area per pass	0.027352	m^2
Water mass velocity (V_t)	42.981529	kg/sm^2
Water Linear Velocity (u_t)	0.04	m/s
Renoyld Number (Re)	860	
Prandtl Number (P_r)	5.695	
L/d_i	114.375	
Tube side coefficient (h_i)	805	$W/m^2.°C$

$$Tube\ Pitch = 1.25\ d_O$$

$$A = \pi dL$$

$$A_C = \frac{\pi}{4d^2}$$

$$Re = \frac{p \times d_i \times u_t}{\mu}$$

$$h_i = \frac{4200(1.35 + 0.02t)ut^{0.8}}{{d_i}^{0.2}}$$

6.1.1.4Bundle and Shell Diameter

Assumptions

$$K_1 = 0.175$$

$$n_1 = 2.285$$

(From table 6 c)

Bundle Dia Clearance (mm) (from fig 6 c)	**BDC**	**76**
Baffle Cut		25%
Heat Transfer Factor (from fig 6 f)	j_h	0.003

Calculations

$$D_b = d_o(\frac{N_t}{K_1})^{1/n_1}$$

Hence Bundle Diameter = **844mm**

$$D_s = BDC + D_b$$

Shell Diameter is therefore **920.433 mm**

$$Baffle\ Spacing = 0.2 \times D_s$$

Hence Baffle Spacing (lb) is **184mm**

To calculate Shell Area

$$A_S = \frac{(p_t - d_o)D_s \times l_b}{p_t}$$

$$A_S = 33887.87\ mm$$

Equivalent Diameter (mm)	**D_e**	**22.19**
Mass Velocity	G_s	442.64
Volumetric Flow rate (kg/hr)	V_s	54000
Velocity (kg/sm^2)	U_s	650.94
Renoyld Number	Re	391,302
Thermal Conductivity (W/m°C)	K_w	29
Prandtl Number	P_r	0.7
Shell Side Coefficient (W/m2°C)	H_s	1,972

For an equilateral triangle pitch arrangement

$$d_e = \frac{4(\frac{p_t}{2} \times 0.87 p_t - \frac{1}{2}\pi \frac{d_O{}^2}{4})}{\pi d_o}$$

$$u_S = \frac{G_s}{\rho}$$

6.1.1.5 Overall Heat Transfer Coefficient

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(\frac{d_o}{d_i})}{h_o} + \frac{d_o}{d_i} \times \frac{1}{h_{id}} + \frac{d_o}{d_i} \times \frac{1}{h_i}$$

Overall Heat Transfer Coefficient	**1/U**	**0.003411859**	
	U	293	W/m^2.°C

6.1.1.6Pressure Drop
Tube Side Pressure Drop Calculation

$$\Delta P_t = N_p(8j_f \times \frac{L}{d_i} \times \frac{\mu^{-m}}{\mu_w} + 2.5) \times \frac{\rho u_t{}^2}{2}$$

$$\Delta P_t = 111\ \frac{N}{m^2}$$

Shell Side Pressure Drop Calculation

$$\Delta P_s = 8j_f \times \frac{D_s}{d_e} \times \frac{L}{l_b} \times \frac{\rho {u_s}^2}{2} \times \frac{\mu^{-0.14}}{\mu_w}$$

Friction Factor	j_f	0.0004	
	ΔP	190.10	kPa

Baffles	Bf	6	
Pressure Drop	ΔP_S	31.68369694	kPa

6.1.2 Waste Heat Recovery Boiler

Service	Boiler
Type	Floating Head Heat Exchanger
Fluid Allocation	Tube Side = Water
	Shell Side = Flue Gases

Tube Side Water

$T_{in} = 165\,°C$ $T_{out} = 201.92\,°C$ $Massflowrate = 4232.34\,\frac{kg}{hr}$

$T_{avg} = 183.46\,°C$

Shell Side Flue Gas

$T_{in} = 450\,°C$ $T_{out} = 210\,°C$ $Massflowrate = 54000\,\frac{kg}{hr}$

$T_{avg} = 330\,°C$

6.1.2.1 Properties of Shell and Tube Side Fluid
Physical Properties of Water

Physical Property	Unit	Tube Side Water
Density (ρ)	kg/m^3	995.00
Specific Heat (C_P)	kJ/kg°C	4.200
Viscosity (μ)	mNs/m^2	0.800
Thermal Conductivity (k)	W/m°C	0.59
Assumption		
No of Passes (N_P)		2
Fouling Factor (h_d) (from table 6 a)	$W/m^2.°C$	3,000

Physical Properties of Flue gas

Physical Property	Unit	Flue Gas
Density (ρ)	kg/m^3	0.68
Specific Heat (C_P)	kJ/kg°C	1.090
Viscosity (μ)	mNs/m2	0.025
Thermal Conductivity (k)	W/m°C	0.0377
Assumption		
No of Passes (N_P)		1
Fouling Factor (h_d) (from table 6 a)	$W/m^2°C$	4,000

We assume our heat transfer coefficient $\boldsymbol{U = 200\,\frac{W}{m^2C}}$ (from table 6 b)

LMTD

$$LMTD = \frac{\Delta T_2 - \Delta T_1}{\ln(\frac{\Delta T_2}{\Delta T_1})}$$

$$\Delta T_1 = 450 - 201.92 = 248°C$$

$$\Delta T_2 = 210 - 165 = 45°C$$

$$LMTD = 118.96°C$$

Corrected LMTD

$$R = \frac{T_1 - T_2}{t_2 - t_1}$$

$$R = 6.5$$

$$S = \frac{t_2 - t_1}{T_2 - T_1}$$

$$S = 0.13$$

$$\Delta T_m = F_t\,\Delta Tl_m$$

$$\Delta T_m = 102.19\ °C$$

Where Ft is found from equation:

Heat Duty and Heat transfer

$$F_t = \frac{\sqrt{(R^2+1)}\ln\left[\frac{(1-S)}{(1-RS)}\right]}{(R-1)\ln\left[\frac{2-S[R+1-\sqrt{(R^2+1)}]}{2-S[R+1+\sqrt{(R^2+1)}]}\right]}$$

$$A = \frac{Q}{U\Delta Tlm}$$

	Units	Tube	Shell
Flow rate (m)	kg/h	4,232.34	54,000
Heat Duty (Q)	kW	182.30	3924

$$A = 192m^2$$

6.1.2.2 Tube Size and Tube Layout

Material of Construction of Tube: Carbon Steel

$$d_O = 30mm$$

$$P_t = triangular\ pitch$$

$$L = 4.880\ m$$

$$BWG = 16$$

$$d_i = 25mm$$

$\boldsymbol{Heat\ Transfer\ Factor = 0.003}$ (From figure 6 b)

Calculations

Tube Pitch (P_t)	**37.500**	
Area of one tube (A_1)	459.696	mm^2
No of tubes (N_t)	418	
Tube/pass (N_P)	2	208.83
Tube cross sectional area (A_C)	490.63	mm^2
Area per pass	0.102457	m^2
Water mass velocity (v_t)	11.474514	kg/sm^2
Water Linear Velocity (u_t)	0.01	m/s
Renoyld Number (Re)	359	
Prandtl Number (Pr)	5.695	
	195.200	
Tube side coefficient (h_i)	338	$W/m^{2}{}^{\circ}C$

$$Tube\ Pitch = 1.25d_O$$

$$A = \pi dL$$

$$Ac = \frac{\pi}{4d^2}$$

$$Re = \frac{p \times d_i \times u_t}{\mu}$$

$$h_i = \frac{4200(1.35 + 0.02t){u_t}^{0.8}}{{d_i}^{0.2}}$$

6.1.2.3 Bundle and Shell Diameter

Assumptions

$$K_1 = 0.249$$

$$n_1 = 2.207$$

(From table 6 c)

Bundle Diameter Clearance (mm) (from fig 6 c)	**BDC**	**96**
Baffle Cut		25%
Heat Transfer Factor (from fig 6 f)	j_h	0.002

Calculations

$$D_b = d_o(\frac{N_t}{K_1})^{1/n_1}$$

Hence Bundle Diameter = **867mm**

$$D_s = BDC + D_b$$

Shell Diameter is therefore **963.383 mm**

$$Baffle\ Spacing = 0.2 \times D_s$$

Hence Baffle Spacing (l_b) is **193mm**

To calculate Shell Area

$$A_s = \frac{(p_t - d_o)D_s \times l_b}{p_t}$$

$$A_s = 37124.27\ mm$$

Equivalent Diameter (mm)	**D_e**	**31.95**
Mass Velocity	G_s	404.05
Flow rate (kg/hr)	V_s	54000
Velocity (kg/sm^2)	U_s	594.19
Renoyld Number	Re	516410
Thermal Conductivity (W/m°C)	K_w	36
Prandtl Number	Pr	0.7
Shell Side Coefficient (W/m^2°C)	H_s	1,805

For an equilateral triangle pitch arrangement

$$d_e = \frac{4(\frac{p_t}{2} \times 0.87p_t - \frac{1}{2}\pi \frac{{d_O}^2}{4})}{\pi d_o}$$

$$us = \frac{G_s}{\rho}$$

6.1.2.4 Overall Heat Transfer Coefficient

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(\frac{d_o}{d_i})}{h_o} + \frac{d_o}{d_i} \times \frac{1}{h_{id}} + \frac{d_o}{d_i} \times \frac{1}{h_i}$$

$$\frac{1}{U} = 0.0048$$

$$U = 207\ \mathrm{W/m^2 °C}$$

6.1.2.5 Pressure Drop

Tube Side Pressure Drop Calculation

$$\Delta P_t = N_p(8j_f \times \frac{L}{d_i} \times \frac{\mu^{-m}}{\mu_w} + 2.5) \times \frac{\rho {u_t}^2}{2}$$

$$\Delta P_t = 69\ \frac{N}{m^2}$$

Shell Side Pressure Drop Calculation

$$\Delta \boldsymbol{P_s} = \boldsymbol{8j_f} \times \frac{\boldsymbol{D_s}}{\boldsymbol{d_e}} \times \frac{\boldsymbol{L}}{\boldsymbol{l_b}} \times \frac{\boldsymbol{\rho u_s}^2}{\boldsymbol{2}} \times \frac{\boldsymbol{\mu^{-0.14}}}{\boldsymbol{\mu_w}}$$

Friction Factor	$\boldsymbol{j_f}$	**0.001**	
	ΔP	733.34	kPa
Baffles	b_f	7	
Pressure Drop	ΔP_s	104.7630823	kPa
New Heat Transfer Coefficient	h_s	1036.413579	$W/m^2 °C$

6.1.3 Condensing Economizer:

Service	**Condensing Economizer**
Type	Floating Head Heat Exchanger
Fluid Allocation	Tube Side = Water
	Shell Side = Flue Gases

Tube Side Water

$$T_{in} = 60\,°C \quad T_{out} = 85\,°C \;\; Massflowrate = 2000\frac{kg}{hr} \qquad T_{avg} = 72.5\,°C$$

Shell Side Flue Gas

$$T_{in} = 184.57\,°C \qquad T_{out} = 141\,°C \qquad Massflowrate = 54000\frac{kg}{hr}$$

$$T_{avg} = 162.5\,°C$$

6.1.3.1 Properties of Shell and Tube Side Fluid
Physical Properties of Water

Physical Property	Unit	Tube Side Water
Density (ρ)	kg/m^3	995.00
Specific Heat (C_P)	kJ/kg°C	4.200
Viscosity (μ)	mNs/m^2	0.800
Thermal Conductivity (k)	W/m°C	0.59
Assumption		
No of Passes (N_P)		2
Fouling Factor (h_d) (from table 6 a)	W/m^2°C	3,000

Physical Properties of Flue gas

Physical Property	Unit	Flue Gas
Density (ρ)	kg/m^3	0.68
Specific Heat (C_P)	kJ/kg°C	1.090
Viscosity (μ)	mNs/m^2	0.025
Thermal Conductivity (k)	W/m°C	0.0377
Assumption		
No of Passes (N_P)		1
Fouling Factor (h_d) (from table 6 a)	W/m^2°C	4,000

We assume our heat transfer coefficient $U = 150\frac{W}{m^2C}$ (from table 6 b)

LMTD

$$LMTD = \frac{\Delta T_2 - \Delta T_1}{\ln(\frac{\Delta T2}{\Delta T1})}$$

$$\Delta T_1 = 184.57 - 85 = 99.57°C$$

$$\Delta T_2 = 110 - 60 = 50°C$$

$$LMTD = 71.96°C$$

Corrected LMTD

$$R = \frac{T_1 - T_2}{t_2 - t_1}$$

$$R = 2.98$$

$$S = \frac{t_2 - t_1}{T_1 - T_2}$$

$$S = 0.20$$

$$\Delta Tm = Ft\ \Delta Tlm$$

$$\Delta Tm = 66.92\ C$$

Where Ft is found from equation:

$$F_t = \frac{\sqrt{(R^2+1)}\ln\left[\frac{(1-S)}{(1-RS)}\right]}{(R-1)\ln\left[\frac{2-S[R+1-\sqrt{(R^2+1)}]}{2-S[R+1+\sqrt{(R^2+1)}]}\right]}$$

6.1.3.2 Heat Duty and Heat transfer Area:

$$Q = mC_P\Delta T$$

$$A = \frac{Q}{U\Delta Tl_m}$$

	Units	Tube	Shell
Flow rate (m)	kg/h	2000	54,000
Heat Duty (Q)	kW	58.33	1219

$$A = 121m^2$$

6.1.3.3 Tube Size and Tube Layout

Material of Construction of Tube: Stainless Steel (SS904 L)

$$do = 25mm$$

$$P_t = triangular\ pitch$$

$$L = 7.320\ m$$

$$BWG = 16$$

$$d_i = 20mm$$

$Heat\ Transfer\ Factor = 0.003$ (From figure 6 b)

Calculations

Tube Pitch (P_t)	**31.250**	
Area of one tube (A_1)	574.620	mm^2
No of tubes (N_t)	211	
Tube/pass (N_P)	2	105.68
Tube cross sectional area (A_C)	314.00	mm^2
Area per pass	0.033184	m^2
Water mass velocity (V_t)	16.741824	kg/sm^2
Water Linear Velocity (u_t)	0.02	m/s
Renoyld Number (Re)	419	
Prandtl Number(Pr)	5.695	
	366.000	
Tube side coefficient (h_i)	246	$W/m^2 °C$

$$Tube\ Pitch = 1.25do$$

$$A = \pi dL$$

$$A_C = \frac{\pi}{4d^2}$$

$$Re = \frac{p \times di \times u_t}{\mu}$$

$$h_i = \frac{4200(1.35 + 0.02t)ut^{0.8}}{di^{0.2}}$$

6.1.3.4 Bundle and Shell Diameter

Assumptions

$$K_1 = 0.249$$

$$n_1 = 2.207$$

(From table 6 c)

Bundle Dia Clearance (mm) (from fig 6 c)	**BDC**	**93**
Baffle Cut		25%
Heat Transfer Factor (from fig 6 f)	j_h	0.003

Calculations

$$D_b = d_o\left(\frac{N_t}{K_1}\right)^{1/n_1}$$

Hence Bundle Diameter = 531mm

$$D_s = BDC + D_b$$

Shell Diameter is therefore 623.887 mm

$$Baffle\ Spacing = 0.2\ \times D_s$$

Hence Baffle Spacing (lb) is 125mm

To calculate Shell Area

$$A_s = \frac{(p_t - d_o)D_s \times l_b}{p_t}$$

$$A_s = 15569.39\ mm^2$$

Equivalent Diameter (mm)	**D_e**	**22.19**
Mass Velocity	G_s	963.43
Flow rate (kg/hr)	V_s	54000
Velocity (kg/sm²)	U_s	1416.81
Renoyld Number	Re	855103
Thermal Conductivity (W/m°C)	K_w	16
Prandtl Number	Pr	0.7
Shell Side Coefficient (W/m²°C)	H_s	4303

For an equilateral triangle pitch arrangement

$$d_e = \frac{4(\frac{p_t}{2} \times 0.87p_t - \frac{1}{2}\pi\frac{d_O{}^2}{4})}{\pi d_o}$$

$$u_s = \frac{G_s}{\rho}$$

6.1.3.5 Overall Heat Transfer Coefficient

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(\frac{d_o}{d_i})}{h_o} + \frac{d_o}{d_i} \times \frac{1}{h_{id}} + \frac{d_o}{d_i} \times \frac{1}{h_i}$$

Overall Heat Transfer Coefficient	**1/U**	**0.006154125**	
	U	162	W/m^2°C

6.1.3.6 Pressure Drop

Tube Side Pressure Drop Calculation

$$\Delta P_t = N_p(8j_f \times \frac{L}{d_i} \times \frac{\mu^{-m}}{\mu_w} + 2.5) \times \frac{\rho u_t{}^2}{2}$$

$$\Delta P_t = 248\frac{N}{m^2}$$

Shell Side Pressure Drop Calculation

$$\Delta P_s = 8j_f \times \frac{D_s}{d_e} \times \frac{L}{l_b} \times \frac{\rho u_S{}^2}{2} \times \frac{\mu^{-0.14}}{\mu_w}$$

Friction Factor	**j_f**	**0.0001**	
	ΔP	900.60	kPa
Baffles	B_f	6	
Pressure Drop	ΔP_s	150.10	kPa
New Heat Transfer Coefficient	H_s	2471.264819	W/m^2°C

6.2 For Heavy Fuel Oil (HFO)

6.2.1 Feed Water Economizer:

Service	**FW ECONOMIZER**
Type	Floating Head Heat Exchanger
Fluid Allocation	Tube Side = Water
	Shell Side = Flue Gases

Tube Side Water

$\boldsymbol{T_{in} = 112\ °C}$ $\boldsymbol{T_{out} = 165\ °C}$ $\boldsymbol{Massflowrate = 4232.34\frac{kg}{hr}}$

$\boldsymbol{T_{avg} = 138.5\ °C}$

Shell Side Flue Gas

$\boldsymbol{T_{in} = 205\ °C}$ $\boldsymbol{T_{out} = 188\ °C}$ $\boldsymbol{Massflowrate = 57600\frac{kg}{hr}}$

$\boldsymbol{T_{avg} = 197\ °C}$

6.2.1.1Properties of Shell and Tube Side Fluid

Physical Properties of Water

Physical Property	Unit	Tube Side Water
Density (ρ)	kg/m^3	995.00
Specific Heat (C_P)	kJ/kg°C	4.200
Viscosity (μ)	mNs/m^2	0.800
Thermal Conductivity (k)	W/m°C	0.59
Assumption		
No of Passes (N_P)		4
Fouling Factor (h_d) (from table 6 a)	W/m^2°C	3,000

Physical Properties of Flue gas

Physical Property	Unit	Flue Gas
Density (ρ)	kg/m^3	0.98
Specific Heat (C_P)	kJ/kg°C	1.110
Viscosity (μ)	mNs/m^2	0.031
Thermal Conductivity (k)	W/m°C	0.0470
Assumption		
No of Passes (N_P)		2
Fouling Factor (h_d) (from table 6 a)	W/m^2°C	4,000

We assume our heat transfer coefficient $\boldsymbol{U = 110\frac{W}{m^2C}}$ (from table 6 b)

LMTD

$$\boldsymbol{LMTD} = \frac{\Delta \boldsymbol{T}_2 - \Delta \boldsymbol{T}_1}{\ln(\frac{\Delta \boldsymbol{T}_2}{\Delta \boldsymbol{T}_1})}$$

$$\Delta \boldsymbol{T}_1 = \mathbf{205 - 165 = 40}°\boldsymbol{C}$$

$$\Delta \boldsymbol{T}_2 = \mathbf{188 - 112 = 76}°\boldsymbol{C}$$

$$\boldsymbol{LMTD} = \mathbf{56.09}°\boldsymbol{C}$$

Corrected LMTD

$$\boldsymbol{R} = \frac{\boldsymbol{T}_1 - \boldsymbol{T}_2}{\boldsymbol{t}_2 - \boldsymbol{t}_1}$$

$$\boldsymbol{R} = \mathbf{0.32}$$

$$\boldsymbol{S} = \frac{\boldsymbol{t}_2 - \boldsymbol{t}_1}{\boldsymbol{T}_1 - \boldsymbol{T}_2}$$

$$\boldsymbol{S} = \mathbf{0.57}$$

$$\Delta \boldsymbol{T}_{\boldsymbol{m}} = \boldsymbol{F}_{\boldsymbol{t}}\, \Delta \boldsymbol{T} \boldsymbol{l}_{\boldsymbol{m}}$$

$$\Delta \boldsymbol{T}_{\boldsymbol{m}} = \mathbf{49}\ °\boldsymbol{C}$$

Where Ft is found from Figure 6 a to be 0.88

6.2.1.2 Heat Duty and Heat transfer Area:

$$\boldsymbol{Q} = \frac{\boldsymbol{U}\boldsymbol{A}}{\Delta \boldsymbol{T} \boldsymbol{l}_{\boldsymbol{m}}}$$

$$\boldsymbol{A} = \frac{\boldsymbol{Q}}{\boldsymbol{U}\Delta \boldsymbol{T} \boldsymbol{l}_{\boldsymbol{m}}}$$

	Units	**Tube**	**Shell**
Flow rate (m)	kg/h	4,232.34	57600
Heat Duty (Q)	kW	261.70	302

$$\boldsymbol{A} = \mathbf{55.61}\boldsymbol{m}^{\mathbf{2}}$$

Tube Size and Tube Layout

Material of Construction of Tube: Carbon Steel

$$d_O = 30mm$$

$$P_t = triangular\ pitch$$

$$L = 1.830\ m$$

$$BWG = 16$$

$$d_i = 25mm$$

$Heat\ Transfer\ Factor = 0.003$ (From figure 6 b)

Calculations

Tube Pitch (P_t)	**37.50**	
Area of one tube (A_1)	172.386	mm^2
No of tubes (N_t)	323	
Tube/pass	4	136.1089124
Tube cross sectional area (A_C)	490.625	mm^2
Area per pass	0.039567	m^2
Water mass velocity (V_t)	29.712566	kg/sm^2
Water Linear Velocity (u_t)	0.03	m/s
Renoyld Number (Re)	929	
Prandtl Number (Pr)	5.695	
L/d_i	73.200	
Tube side coefficient (h_i)	548	$W/m^2°C$

$$Tube\ Pitch = 1.25d_o$$

$$A = \pi dL$$

$$Ac = \frac{\pi}{4d^2}$$

$$Re = \frac{p \times d_i \times u_t}{\mu}$$

$$h_i = \frac{4200(1.35 + 0.02t){u_t}^{0.8}}{di^{0.2}}$$

6.2.1.3 Bundle and Shell Diameter

Assumptions

$$K_1 = 0.175$$

$$n_1 = 2.285$$

(From table 6 c)

Bundle Dia Clearance (mm) (from fig 6 c)	**BDC**	**90**
Baffle Cut		25%
Heat Transfer Factor (from fig 6 f)	j_h	0.03

Calculations

$$D_b = d_o\left(\frac{N_t}{K_1}\right)^{1/n_1}$$

Hence Bundle Diameter = 806mm

$$D_s = BDC + D_b$$

Shell Diameter is therefore 895.884 mm

$$Baffle\ Spacing = 0.2\ \times D_s$$

Hence Baffle Spacing (l_b) is 179mm

To calculate Shell Area

$$A_s = \frac{(p_t - d_o)D_s \times l_b}{p_t}$$

$$A_s = 32104.30\ mm$$

Equivalent Diameter (mm)	**D_e**	**31.95**
Mass Velocity	G_s	498.38
Volumetric Flow rate (kg/hr)	V_s	57600
Velocity (kg/sm^2)	U_s	508.55
Renoyld Number	Re	513685
Thermal Conductivity (W/m°C)	K_w	30
Prandtl Number	Pr	0.7
Shell Side Coefficient (W/m^2°C)	h_s	2247

For an equilateral triangle pitch arrangement

$$d_e = \frac{4(\frac{p_t}{2} \times 0.87 p_t - \frac{1}{2}\pi \frac{{d_O}^2}{4})}{\pi d_o}$$

$$u_s = \frac{G_s}{\rho}$$

6.2.1.4Overall Heat Transfer Coefficient

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(\frac{d_o}{d_i})}{h_o} + \frac{d_o}{d_i} \times \frac{1}{h_{id}} + \frac{d_o}{d_i} \times \frac{1}{h_i}$$

Overall Heat Transfer Coefficient	**1/U**	**0.003376559**	
	U	296	W/m²°C

6.2.1.5 Pressure Drop

Tube Side Pressure Drop Calculation

$$\Delta P_t = N_p(8 j_f \times \frac{L}{d_i} \times \frac{\mu^{-m}}{\mu_w} + 2.5) \times \frac{\rho {u_t}^2}{2}$$

$$\Delta P_t = 9 \frac{N}{m^2}$$

Shell Side Pressure Drop Calculation

$$\Delta P_s = 8 j_f \times \frac{D_s}{d_e} \times \frac{L}{l_b} \times \frac{\rho {u_s}^2}{2} \times \frac{\mu^{-0.14}}{\mu_w}$$

Friction Factor	j_f	**0.0004**	
Pressure Drop	ΔP	116,125	N/m²
		116.13	kPa
		16.84	Psi
Baffles	B_f	6	
Pressure Drop	ΔP_s	19.35423341	kPa
		19354.23341	N/m²
		2.807093127	Psi
New Heat Transfer Coefficient	h_s	1290.759154	W/m²°C

6.2.2 Waste Heat Recovery Boiler

Service	Boiler
Type	Floating Head Heat Exchanger
Fluid Allocation	Tube Side = Water
	Shell Side = Flue Gases

Tube Side Water

$T_{in} = 165\,°C$ $T_{out} = 201.92\,°C$ $Massflowrate = 4232.34\,\frac{kg}{hr}$

$T_{avg} = 183.46\,°C$

Shell Side Flue Gas

$T_{in} = 380\,°C$ $T_{out} = 205\,°C$ $Massflowrate = 57600\,\frac{kg}{hr}$

$T_{avg} = 292.5\,°C$

6.2.2.1Properties of Shell and Tube Side Fluid
Physical Properties of Water

Physical Property	Unit	Tube Side Water
Density (ρ)	kg/m^3	995.00
Specific Heat (C_P)	kJ/kg°C	4.200
Viscosity (μ)	mNs/m^2	0.800
Thermal Conductivity (k)	W/m°C	0.59
Assumption		
No of Passes (N_P)		2
Fouling Factor (h_d) (from table 6 a)	W/m^2°C	3,000

Physical Properties of Flue gas

Physical Property	Unit	Flue Gas
Density (ρ)	kg/m^3	0.98
Specific Heat (C_P)	kJ/kg°C	1.110
Viscosity (μ)	mNs/m^2	0.031
Thermal Conductivity (k)	W/m°C	0.0470
Assumption		
No of Passes (N_P)		1
Fouling Factor (h_d) (from table 6 a)	W/m^2°C	4,000

We assume our heat transfer coefficient $U = 200\,\frac{W}{m^2C}$ (from table 6 b)

LMTD

$$LMTD = \frac{\Delta T_2 - \Delta T_1}{\ln(\frac{\Delta T_2}{\Delta T_1})}$$

$$\Delta T_1 = 380 - 201.92 = 178.08°C$$

$$\Delta T_2 = 205 - 165 = 40°C$$

$$LMTD = 92.4°C$$

Corrected LMTD

$$R = \frac{T_1 - T_2}{t_2 - t_2}$$

$$R = 04.74$$

$$S = \frac{t_2 - t_1}{t_1 - t_2}$$

$$S = 0.17$$

$$\Delta T_m = F_t \Delta T l_m$$

$$\Delta T_m = 77.67\,°C$$

Where Ft is found from equation:

$$F_t = \frac{\sqrt{(R^2+1)}\ln\left[\frac{(1-S)}{(1-RS)}\right]}{(R-1)\ln\left[\frac{2-S[R+1-\sqrt{(R^2+1)}]}{2-S[R+1+\sqrt{(R^2+1)}]}\right]}$$

6.2.2.2Heat Duty and Heat transfer Area:

$$Q = mC_p\Delta T$$

$$A = \frac{Q}{U\Delta T l_m}$$

	Units	Tube	Shell
Flow rate (m)	kg/h	4,232.34	57600
Heat Duty (Q)	kW	182.30	3108

$$A = 200m^2$$

Tube Size and Tube Layout

Material of Construction of Tube: Carbon Steel

$$d_O = 30mm$$

$$P_t = triangular\ pitch$$

$$L = 6.100\ m$$

$$BWG = 16$$

$$d_i = 25mm$$

$Heat\ Transfer\ Factor = 0.04$ (From figure 6 b)

Calculations

Tube Pitch (P_t)	**37.50**	
Area of one tube (A_1)	574.620	mm^2
No of tubes (N_t)	348	
Tube/pass	2	136.1089124
Tube cross sectional area (A_C)	490.63	mm^2
Area per pass	0.085417	m^2
Water mass velocity (V_t)	13.765	kg/sm^2
Water Linear Velocity (u_t)	0.01	m/s
Renoyld Number (Re)	430	
Prandtl Number (Pr)	5.695	
L/d_i	244	
Tube side coefficient (h_i)	361	$W/m^2°C$

$$Tube\ Pitch = 1.25d_O$$

$$A = \pi dL$$

$$A_C = \frac{\pi}{4d^2}$$

$$Re = \frac{p \times d_i \times u_t}{\mu}$$

$$h_i = \frac{4200(1.35 + 0.02t){u_t}^{0.8}}{di^{0.2}}$$

6.2.2.3Bundle and Shell Diameter

Assumptions

$$K_1 = 0.249$$

$$n_1 = 2.207$$

(From table 6 c)

Bundle Dia Clearance (mm) (from fig 6 c)	**BDC**	**85**
Baffle Cut		25%
Heat Transfer Factor (from fig 6 f)	j_h	0.03

Calculations

$$D_b = d_o(\frac{N_t}{K_1})^{1/n_1}$$

Hence Bundle Diameter = 799mm

$$D_s = BDC + D_b$$

Shell Diameter is therefore 883.758 mm

$$Baffle\ Spacing = 0.2\ \times D_s$$

Hence Baffle Spacing (l_b) is 177mm

To calculate Shell Area

$$A_s = \frac{(p_t - d_o)D_s \times l_b}{p_t}$$

$$A_s = \ 31241.11\ mm$$

Equivalent Diameter (mm)	D_e	**31.95**
Mass Velocity	G_s	512.15
Volumetric Flow rate (kg/hr)	V_s	57600
Velocity (kg/sm^2)	U_s	522.60
Renoyld Number	Re	529586
Thermal Conductivity (W/m°C)	K_w	36
Prandtl Number	Pr	0.7
Shell Side Coefficient (W/m^2°C)	H_s	28054

For an equilateral triangle pitch arrangement

$$d_e = \frac{4(\frac{p_t}{2} \times 0.87p_t - \frac{1}{2}\pi\frac{{d_O}^2}{4})}{\pi d_o}$$

$$u_s = \frac{G_s}{\rho}$$

6.2.2.4Overall Heat Transfer Coefficient

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(\frac{d_o}{d_i})}{h_o} + \frac{d_o}{d_i} \times \frac{1}{h_{id}} + \frac{d_o}{d_i} \times \frac{1}{h_i}$$

Overall Heat Transfer Coefficient	**1/U**	**0.0040894**	
	U	245	W/m²°C

6.2.2.5Pressure Drop
Tube Side Pressure Drop Calculation

$$\Delta P_t = N_p(8j_f \times \frac{L}{d_i} \times \frac{\mu^{-m}}{\mu_w} + 2.5) \times \frac{\rho {u_t}^2}{2}$$

$$\Delta P_t = 149\frac{N}{m^2}$$

Shell Side Pressure Drop Calculation

$$\Delta P_s = 8j_f \times \frac{D_s}{d_e} \times \frac{L}{l_b} \times \frac{\rho {u_s}^2}{2} \times \frac{\mu^{-0.14}}{\mu_w}$$

Friction Factor	j_f	**0.0004**	
Pressure Drop	ΔP	408,770	N/m^2
		408.77	kPa
		59.29	Psi
Baffles	B_f	6	
Pressure Drop	ΔP_s	68.1283881	kPa
		68128.3881	N/m^2
		9.881183406	Psi

6.2.3 Condensing Economizer:

Service	Condensing Economizer
Type	Floating Head Heat Exchanger
Fluid Allocation	Tube Side = Water
	Shell Side = Flue Gases

Tube Side Water

$\boldsymbol{Tin = 60C}$ $\boldsymbol{Tout = 85C}$ $\boldsymbol{Massflowrate = 2000\frac{kg}{hr}}$ $\boldsymbol{Tavg = 72.5C}$

Shell Side Flue Gas

$\boldsymbol{Tin = 188.05C}$ $\boldsymbol{Tout = 159C}$ $\boldsymbol{Massflowrate = 57600\frac{kg}{hr}}$

$\boldsymbol{Tavg = 173.5C}$

6.2.3.1Properties of Shell and Tube Side Fluid

Physical Properties of Water

Physical Property	Unit	Tube Side Water
Density (ρ)	kg/m^3	995.00
Specific Heat (C_P)	kJ/kg°C	4.200
Viscosity (μ)	mNs/m^2	0.800
Thermal Conductivity (k)	W/m°C	0.59
Assumption		
No of Passes (N_P)		2
Fouling Factor (h_d) (from table 6 a)	$W/m^2°C$	3,000

Physical Properties of Flue gas

Physical Property	Unit	Flue Gas
Density (ρ)	kg/m^3	0.98
Specific Heat (C_P)	kJ/kg°C	1.060
Viscosity (μ)	mNs/m^2	0.024
Thermal Conductivity (k)	W/m°C	0.036
Assumption		
No of Passes (N_P)		1
Fouling Factor (h_d) (from table 6 a)	$W/m^2°C$	4,000

We assume our heat transfer coefficient $U = 150 \frac{W}{m^2C}$ (from table 6 b)

LMTD

$$LMTD = \frac{\Delta T_2 - \Delta T_1}{\ln(\frac{\Delta T_2}{\Delta T_1})}$$

$$LMTD = 73.36°C$$

Corrected LMTD

$$R = \frac{T_1 - T_2}{t_2 - t_2}$$

$$R = 3.12$$

$$S = \frac{t_2 - t_1}{T_1 - T_2}$$

$$S = 0.20$$

$$\Delta T_m = F_t \, \Delta Tl_m$$

$$\Delta T_m = 67.49 \, °C$$

Where F_t is found from equation:

$$F_t = \frac{\sqrt{(R^2+1)} \ln\left[\frac{(1-S)}{(1-RS)}\right]}{(R-1)\ln\left[\frac{2-S[R+1-\sqrt{(R^2+1)}]}{2-S[R+1+\sqrt{(R^2+1)}]}\right]}$$

6.2.3.2 Heat Duty and Heat transfer Area:

$$Q = \frac{UA}{\Delta Tl_m}$$

$$A = \frac{Q}{U \Delta Tl_m}$$

	Units	Tube	Shell
Flow rate (m)	kg/h	2000	57600
Heat Duty (Q)	kW	58.33	1324

$$A = 131m^2$$

6.2.3.3Tube Size and Tube Layout

Material of Construction of Tube: Stainless Steel SS904L

$$d_O = 25mm$$

$$P_t = triangular\ pitch$$

$$L = 6.100\ m$$

$$BWG = 16$$

$$d_i = 20mm$$

$Heat\ Transfer\ Factor = 0.09$ (From figure 6 b)

Calculations

Tube Pitch (P$_t$)	**31.250**	
Area of one tube (A$_1$)	478.58	mm^2
No of tubes (N$_t$)	273	
Tube/pass	2	136.1089124
Tube cross sectional area (A$_C$)	314	mm^2
Area per pass	0.0428	m^2
Water mass velocity (V$_t$)	12.95	kg/sm^2
Water Linear Velocity (u$_t$)	0.01	m/s
Renoyld Number (Re)	324	
Prandtl Number (Pr)	5.695	
L/d$_i$	305	
Tube side coefficient (h$_i$)	200	W/m^2°C

$$Tube\ Pitch = 1.25d_O$$

$$A = \pi dL$$

$$Ac = \frac{\pi}{4d^2}$$

$$Re = \frac{p \times d_i \times u_t}{\mu}$$

$$h_i = \frac{4200(1.35 + 0.02t){u_t}^{0.8}}{{d_i}^{0.2}}$$

6.2.3.4Bundle and Shell Diameter

Assumptions

$$K_1 = 0.249$$

$$n_1 = 2.207$$

(from table 6 c)

Bundle Dia Clearance (mm) (from fig 6 c)	**BDC**	**90**
Baffle Cut		25%
Heat Transfer Factor (from fig 6 f)	j_h	0.04

Calculations

$$D_b = d_o(\frac{N_t}{K_1})^{1/n_1}$$

Hence Bundle Diameter = 596mm

$$D_s = BDC + D_b$$

Shell Diameter is therefore 686.232 mm

$$Baffle\ Spacing = 0.2\ \times D_s$$

Hence Baffle Spacing (lb) is 137mm

To calculate Shell Area

$$A_s = \frac{(p_t - d_o)D_s \times l_b}{p_t}$$

$$A_s = 18836\ mm$$

Equivalent Diameter (mm)	**D_e**	**22.19**
Mass Velocity	G_s	849.41
Flow rate (kg/hr)	V_s	57600
Velocity (kg/sm^2)	U_s	866.75
Renoyld Number	Re	775622
Thermal Conductivity (W/m°C)	K_w	16
Prandtl Number	Pr	0.7
Shell Side Coefficient (W/m^2°C)	H_s	101296

For an equilateral triangle pitch arrangement

$$d_e = \frac{4(\frac{p_t}{2} \times 0.87 p_t - \frac{1}{2}\pi \frac{{d_O}^2}{4})}{\pi d_o}$$

$$u_s = \frac{G_s}{\rho}$$

6.2.3.5Overall Heat Transfer Coefficient

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(\frac{d_o}{d_i})}{h_o} + \frac{d_o}{d_i} \times \frac{1}{h_{id}} + \frac{d_o}{d_i} \times \frac{1}{h_i}$$

Overall Heat Transfer Coefficient	**1/U**	**0.007087288**	
	U	141	W/m^2°C

6.2.3.6Pressure Drop
Tube Side Pressure Drop Calculation

$$\Delta P_t = N_p(8j_f \times \frac{L}{d_i} \times \frac{\mu^{-m}}{\mu_w} + 2.5) \times \frac{\rho {u_t}^2}{2}$$

$$\Delta P_t = 17 \frac{N}{m^2}$$

Shell Side Pressure Drop Calculation

$$\Delta P_s = 8j_f \times \frac{D_s}{d_e} \times \frac{L}{l_b} \times \frac{\rho {u_s}^2}{2} \times \frac{\mu^{-0.14}}{\mu_w}$$

Friction Factor	j_f	**0.0002**	
Pressure Drop	ΔP	809,580	N/m^2
		809.58	kPa
		117.42	Psi
Baffles	B_f	7	
Pressure Drop	ΔP_s	115.6542931	kPa
		115654.2931	N/m^2
		16.77423044	Psi
New Heat Transfer Coefficient	H_s	58179.33953	W/m^2°C

6.3 Boiler Specifications:

6.3.1. Required power for steam production

$$Mass\ Flowrate = 4232.344\ kg/hr$$

Using steam tables:

$$H\ steam\ at\ 201.924°C = 2793\frac{kJ}{kg}$$

$$H\ Saturated\ water\ at\ 201.924°C = 861.067\frac{kJ}{kg}$$

$$For\ power = mC_p\Delta T + m\Delta H$$

$$m = 4232.34\frac{kg}{hr}$$

$$Average\ C_p = 4.26\frac{J}{Kg.K}$$

$$Temperature\ Change: 37°C$$

$$\Delta H = Hsteam - Hwater$$

$$\Delta H = 2793 - 861.067 = 1931.933\frac{kJ}{kg}$$

Hence,

$$Power = (4234.34 \times 4.26 \times 37) + (4232.34 \times 1931.933)$$

$$Power = 2271.46kW$$

6.3.2. Operating Pressure

From steam table:

$$Pressure\ at\ 201.924°C = 15.169\ barG$$

Hence,

$$Operating\ Pressure = 15.169\ barG$$

6.3.3. Internal thickness

We suppose that the boiler runs for 24 hours a day

$$\boldsymbol{m = 4232.34\,\frac{kg}{hr}}$$

$$\boldsymbol{\rho\ of\ water = 1000\,\frac{kg}{m^3}}$$

$$\boldsymbol{Volume\ of\ vessel = \frac{4232.34 \times 24}{1000}}$$

$$\boldsymbol{Volume = 101.5\ m^3}$$

If we assume that the water level is 85%

$$\boldsymbol{Volume = 119.4\ m^3}$$

For radius,

$$\boldsymbol{Volume = \pi \times r^2 \times h}$$

$$\boldsymbol{Estimated\ radius = 1.3m}$$

$$\boldsymbol{h = \frac{119.4}{1.3^2 \times \pi}}$$

$$\boldsymbol{h = 22.5\ m}$$

For calculations of the minimum thickness for the vessel,

$$\boldsymbol{t = \frac{PR}{SE - 0.6P}}$$

Where,

P = internal design pressure (N/m^2) = 15.169 barG = 220.399psi

S = maximum stress for carbon steel (N/m^2)

E = efficiency of weld joints or of ligaments between openings

R = shell internal radius = 1.3 m = 51.18 in

From literature:

S= 17500 psi

E= 100%

$$t = \frac{220.399 \times 51.18}{17500 - 0.6 \times 220.399}$$

$$t = 0.649\ in = 14.49\ mm$$

Allowances for corrosion are incorporated through a corrosion factor which according to ASME BPV code is 0.079 in

Hence,

$$t = 0.649 + 0.079$$

$$t = 0.728\ in = 18.49\ mm$$

6.3.4. Design Pressure

The design pressure is usually 10% greater than the maximum operating pressure.

Hence

$$Design\ Pressure = \frac{15.169}{0.9}$$

$$Design\ Pressure = 16.85 bar = 244.887\ psi$$

6.3.5 Minimum thickness with respect to design pressure

$$t = \frac{PR}{SE - 0.6P}$$

$$t = \frac{244.86 \times 51.18}{(17500 - 0.6 \times 244.87)}$$

$$t = 0.722 in = 18.33\ mm$$

For corrosion:

$$t = 0.722 + 0.079$$

$$t = 20.34\ mm$$

6.3.6. Maximum available pressure

$$Maximum\ Pressure = \frac{ESt}{R + 0.6t}$$

$$Maximum\ Pressure = \frac{17500 \times 0.72}{51.18 + 0.6 \times 0.72}$$

$$Maximum\ Pressure = 244.129\ psi = 16.90\ barG$$

TABLES:

Fluid	Coefficient (W/m^2°C)	Factor (resistance) (m^2°C/W)
River water	3000–12,000	0.0003–0.0001
Sea water	1000–3000	0.001–0.0003
Cooling water (towers)	3000–6000	0.0003–0.00017
Towns water (soft)	3000–5000	0.0003–0.0002
Towns water (hard)	1000–2000	0.001–0.0005
Steam condensate	1500–5000	0.00067–0.0002
Steam (oil free)	4000–10,000	0.0025–0.0001
Steam (oil traces)	2000–5000	0.0005–0.0002
Refrigerated brine	3000–5000	0.0003–0.0002
Air and industrial gases	5000–10,000	0.0002–0.0001
Flue gases	2000–5000	0.0005–0.0002
Organic vapours	5000	0.0002
Organic liquids	5000	0.0002
Light hydrocarbons	5000	0.0002
Heavy hydrocarbons	2000	0.0005
Boiling organics	2500	0.0004
Condensing organics	5000	0.0002
Heat transfer fluids	5000	0.0002
Aqueous salt solutions	3000–5000	0.0003–0.0002

Table 6 (a) Fouling factors typical values

Triangular pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.319	0.249	0.175	0.0743	0.0365
n_1	2.142	2.207	2.285	2.499	2.675
Square pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.215	0.156	0.158	0.0402	0.0331
n_1	2.207	2.291	2.263	2.617	2.643

Table 6 b Typical Tube Arrangements and Constants for use

Shell and tube exchangers

Hot fluid	Cold fluid	U (W/m^2°C)
Heat exchangers		
Water	Water	800–1500
Organic solvents	Organic solvents	100–300
Light oils	Light oils	100–400
Heavy oils	Heavy oils	50–300
Gases	Gases	10–50
Coolers		
Organic solvents	Water	250–750
Light oils	Water	350–900
Heavy oils	Water	60–300
Gases	Water	20–300
Organic solvents	Brine	150–500
Water	Brine	600–1200
Gases	Brine	15–250
Heaters		
Steam	Water	1500–4000
Steam	Organic solvents	500–1000
Steam	Light oils	300–900
Steam	Heavy oils	60–450
Steam	Gases	30–300
Dowtherm	Heavy oils	50–300
Dowtherm	Gases	20–200
Flue gases	Steam	30–100
Flue	Hydrocarbon vapours	30–100
Condensers		
Aqueous vapours	Water	1000–1500
Organic vapours	Water	700–1000
Organics (some non-condensables)	Water	500–700
Vacuum condensers	Water	200–500
Vaporisers		
Steam	Aqueous solutions	1000–1500
Steam	Light organics	900–1200
Steam	Heavy organics	600–900

Table 6 c Typical Overall Coefficients

FIGURES

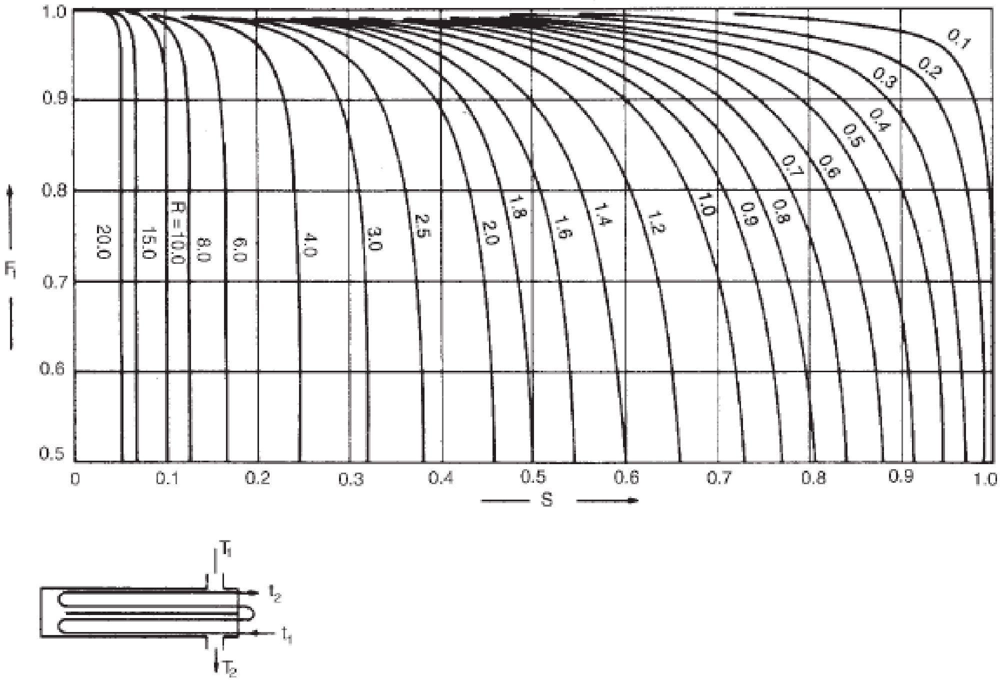


Fig 6 (a) Temperature Correction Factor: 2 shell passes; 4 or multiple of 4 tube passes

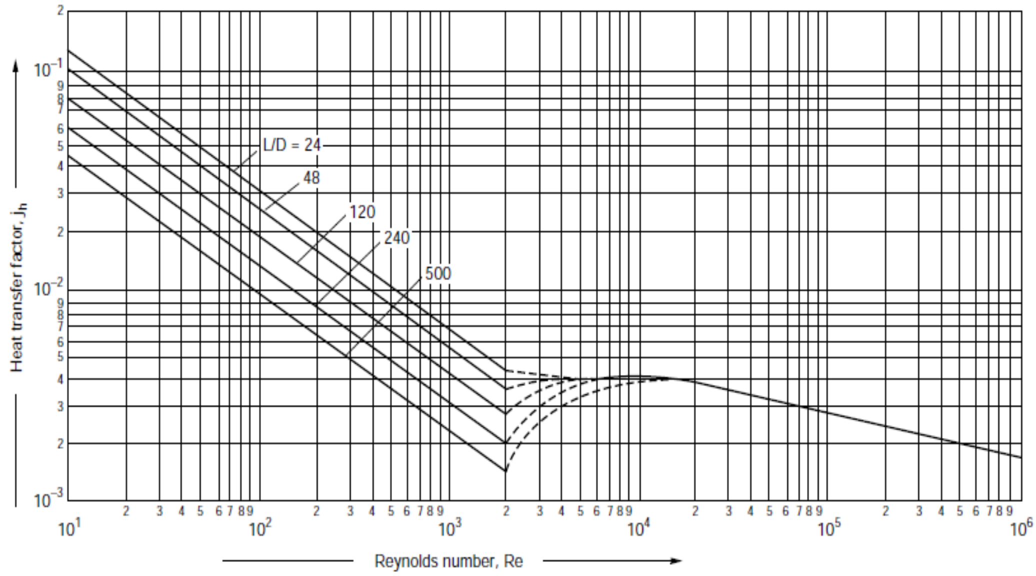


Fig 6 (b) Tube Side Heat Transfer Factor

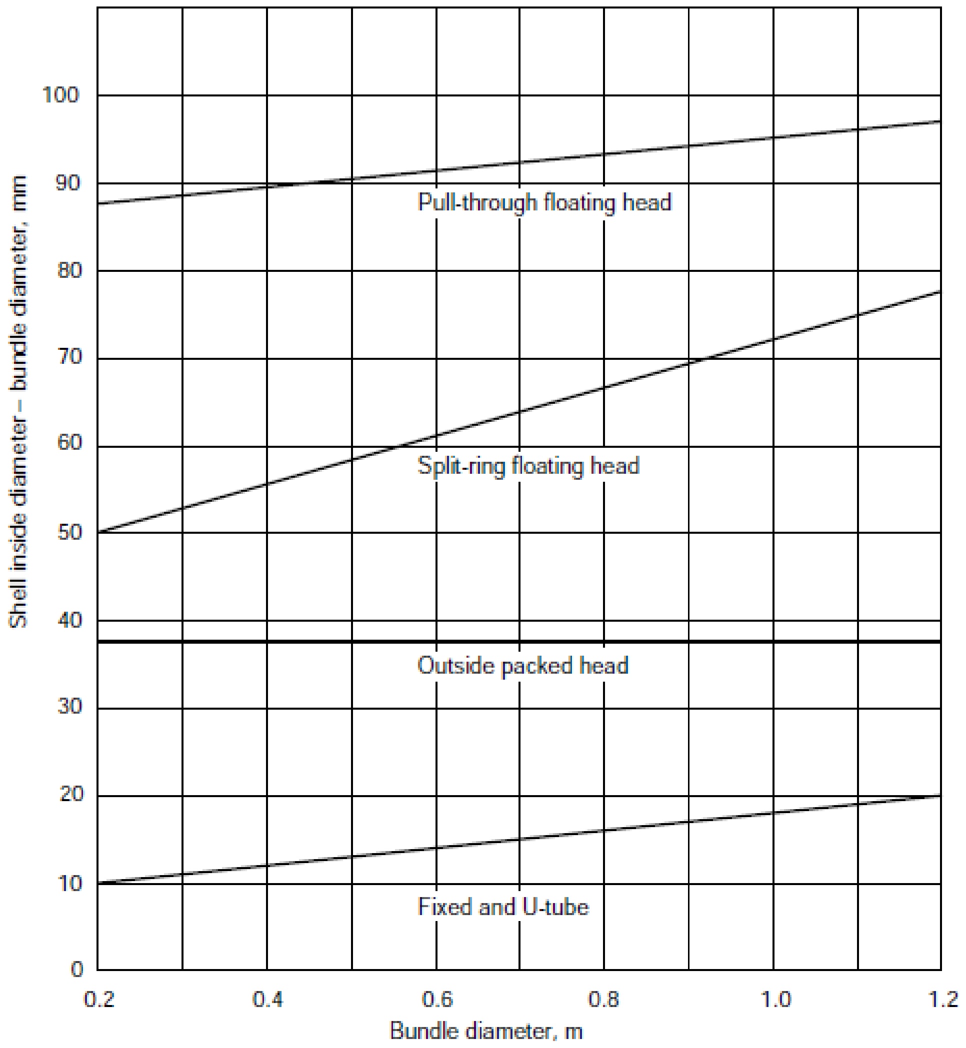


Fig 6 (c) Shell Bundle Clearance

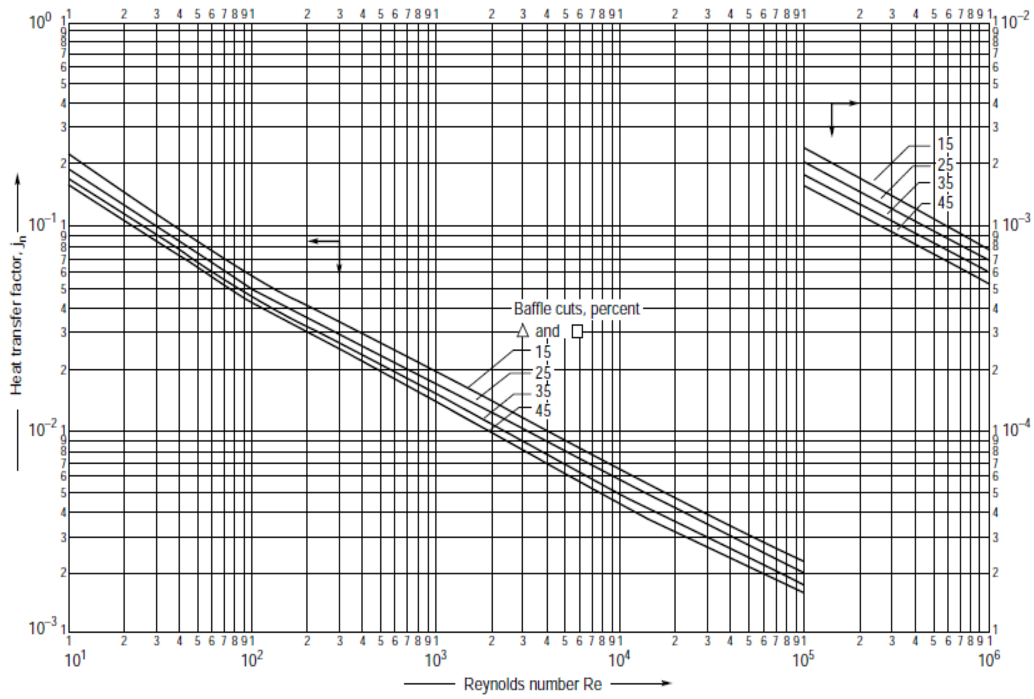


Figure 12.29. Shell-side heat-transfer factors, segmental baffles

Fig 6 (d) Shell side Heat Transfer Factor

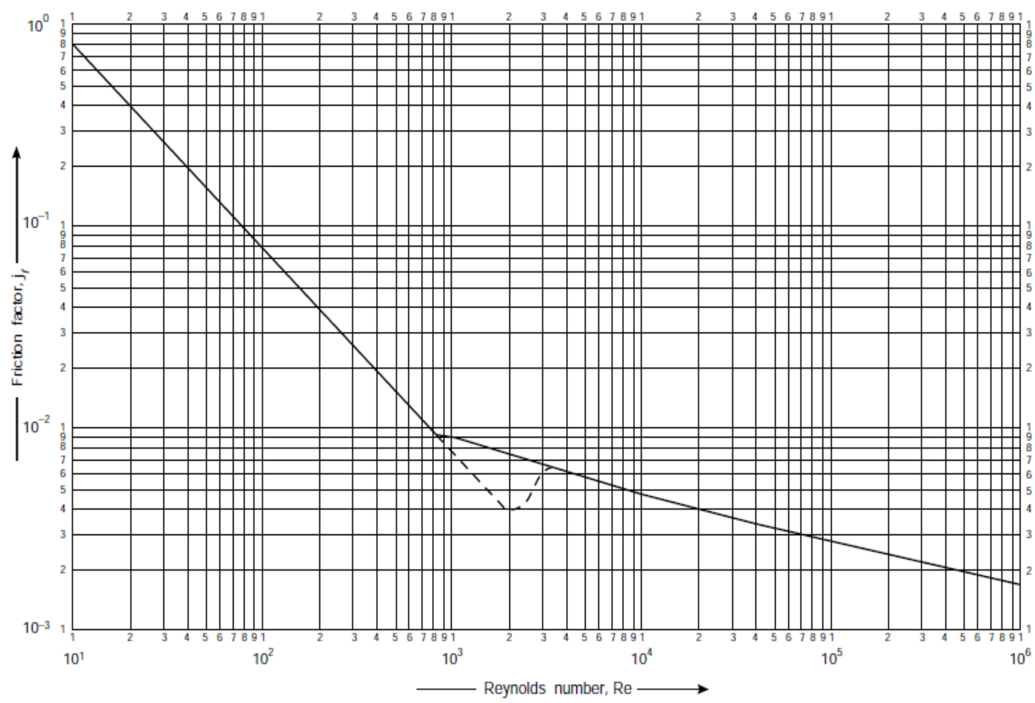


Fig 6 (e) Tube side Friction Factor

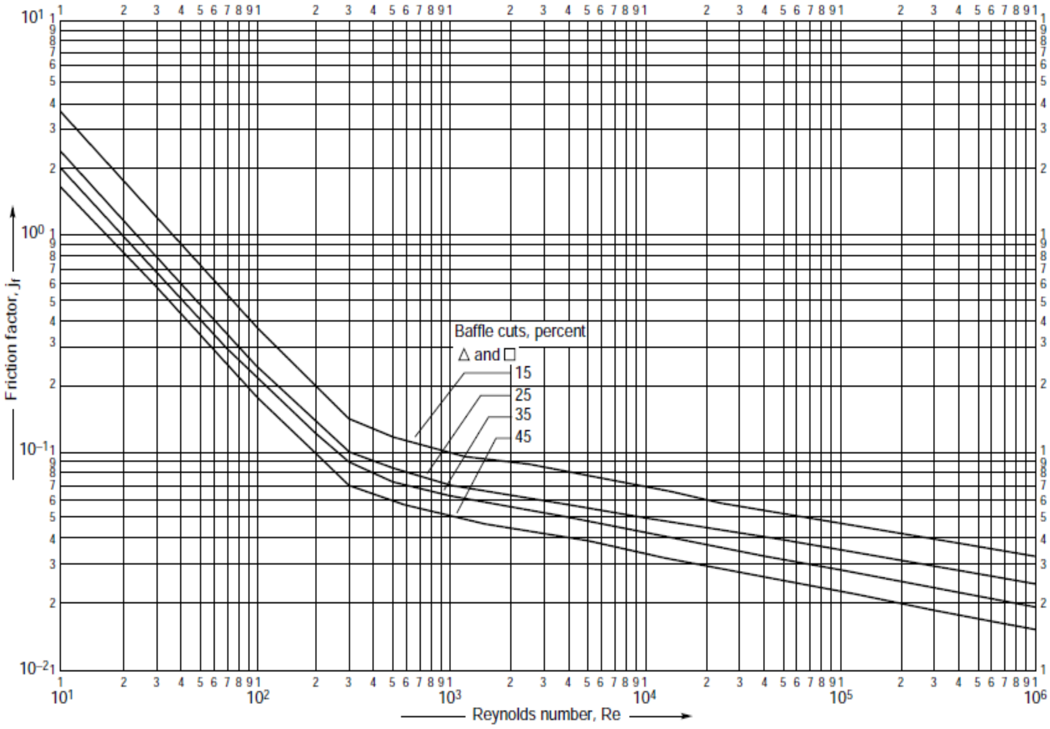


Fig 6 (f) Shell side Friction Factor

7 Economic evaluation

7.1 Condensing Economizer for NG

Cost of Equipment

$$\boldsymbol{Area = 121\ m^2}$$

$$\boldsymbol{Cost =\ 100,000}\$$$

$$\boldsymbol{Purchase\ Cost = Cost\ \times Pressure\ factor}$$

$$\boldsymbol{= 100000 \times 1.1 \times 1}$$

$$\boldsymbol{= \$\ 110,000}$$

The cost of erection, piping and instrumentation are the additional costs on equipment

Using Lang's factors to calculate the cost

$$\boldsymbol{Physical\ Cost = Purchase\ Cost\ (1 + 0.4 + 0.2 + 0.2)}$$

$$\boldsymbol{= 110000 \times 1.8}$$

$$\boldsymbol{= \$\ 198,000}$$

Now adding the contingency and contractor's fee

$$\boldsymbol{Total\ Cost = Physical\ Cost\ \times (1 + 0.1 + 0.05)}$$

$$\boldsymbol{= 198000 \times 1.15}$$

$$\boldsymbol{= \$227,700}$$

Adding the working capital now

$$\boldsymbol{Working\ Capital = 0.05 \times 227000}$$

$$\boldsymbol{= \$11385}$$

$$\boldsymbol{Total\ Investment = working\ capital + Total\ Cost}$$

$$\boldsymbol{= 227700 + 11385}$$

$$\boldsymbol{= \$\ 239,085}$$

7.2 Condensing Economizer for HFO

$$\boldsymbol{Area = 131\ m^2}$$

$$\boldsymbol{Cost = \$\ 120,000}$$

$$Purchase\ Cost = Cost\ \times Pressure\ factor$$
$$= 120000 \times 1.1 \times 1$$
$$= \$\ 132,000$$

The cost of erection, piping and instrumentation are the additional costs on equipment

Using Lang's factors to calculate the cost

$$Physical\ Cost = Purchase\ Cost\ (1 + 0.4 + 0.2 + 0.2)$$
$$= 132000 \times 1.8$$
$$= \$\ 237,600$$

Now adding the contingency and contractor's fee

$$Total\ Cost = Physical\ Cost\ \times (1 + 0.1 + 0.05)$$
$$= 237600 \times 1.15$$
$$= \$273,240$$

Adding the working capital now

$$Working\ Capital = 0.05 \times 273240$$
$$= \$13662$$

$$Total\ Investment = working\ capital + Total\ Cost$$
$$= 227700 + 11385$$
$$= \$\ 286,902$$

7.3 Rate of Return Calculation

Fuel	Btu in fuel	Rate ($ / MMBtu, Ltr)	Rate ($/MMBtu)
Natural Gas (MMBtu)	1,000,000	8.35	8.35
H.F.O (Liters)	40,786	0.41	10.05

7.4 Steam Cost for N.G Condenser

$$C_F = \frac{a_F(H_s - h_W)}{1000 \times \eta_B}$$
$$= \frac{8.35(1200.85 - 198.5)}{1000 \times 0.86}$$

$$= \$\,9.73\big/_{1000\ lb}$$

$$C_G = 1.30 \times 9.73$$

$$= {}^{\$\,12.65}\big/_{1000\ lb}$$

$$= {}^{\$\,0.0316}\big/_{kg}$$

$$Steam\ Saving = 125.7\,\frac{kg}{hr}$$

$$Per\ Year\ Saving = 0.0316 \times 125.7 \times 24 \times 365$$

$$= \$\,34{,}795.77$$

$$Payback\ Period = \frac{239085}{34795.77}$$

$$= 6.87\ years$$

7.5 Steam Cost for HFO Condenser

$$C_F = \frac{a_F(H_s - h_W)}{1000 \times \eta_B}$$

$$= \frac{10.05(1200.85 - 198.5)}{1000 \times 0.86}$$

$$= \$\,13.25\big/_{1000\ lb}$$

$$C_G = 1.30 \times 13.25$$

$$= {}^{\$\,17.23}\big/_{1000\ lb}$$

$$= {}^{\$\,0.043}\big/_{kg}$$

$$Steam\ Saving = 125.7\,\frac{kg}{hr}$$

$$Per\ Year\ Saving = 0.043 \times 125.7 \times 24 \times 365$$

$$= \$\,47{,}434.53$$

$$Payback\ Period = \frac{286902}{47434.53}$$

$$= 6.05\ years$$

8 Instrumentation and Process Control

8.1 Introduction

Instrumentation is a fundamental requisite to control any process system. The control can be applied automatically, semi-automatically or manually. The quality of the product depends upon the quality of control applied and it bears a relationship to the accuracy of the measurement methods which are used. The controls are basically applied on four parameters which are flow, temperature, pressure and level. Therefore, effective means of measurement is an integral part of the design and formulation of any process control system.

8.1.1 Temperature Measurement and Control

The temperature measure is applied to each equipment where there is variation of temperature due to heat transfer between the streams. The inlet and outlet temperatures of equipment such as heat exchangers, condensers, deaerator and boiler are measured to ensure the routine process is going on and there are no discrepancies due to problem in any equipment. Most of the temperature gauges are thermocouples which facilitate measurements to a centralized location. For higher accuracy of measurements, resistance thermometers are used.

8.1.2 Pressure Measurement and Control

Most of the process systems use pressurized equipment and vessel to maintain a certain environment within vessels. It is a valuable indication of what is the state and composition of the monitored stream. Different equipment including turbines, compressors and pumps and flash vessels which deal with the pressure changes of the fluid, are equipped with pressure measuring devices. It signifies the changes in energy and determines the energy held by each stream.

The pressure gauges installed in industry are either elastic element type used to have local readings as well as transmit data to the centralized control room. Other extensively used industrial pressure element is the Diaphragm or Bellow gauges.

8.1.3 Measurements and Control

Flow measurements are the most important part of the process control when it comes to determine the economic aspects of a plant. Flow indicators meters the various streams to ensure that the designed values are being achieved while processing and also to calculate different utility consumptions to calculate the utility costs and efficiencies. The flow indication is usually done using variable head devices and to some special cases where a high pressure drop is affordable, variable area devices like rotameter is also used.

8.1.4 Level Measurements and Control

Level measurements and instrumentations is an important control of the intermediate storage devices, flash vessels and storage tanks where hold up is required to process the liquid. The level is measured via two types of methods: Difference in static pressure of fluid and use of a wet able material to determine the height of the fluid. Another traditional method still applied in few tanks which are in remote areas relevant to the control rooms are measured for level via dip method. This method is usually used to calculate the amount of diesel and fuel storage tanks and is a good method in case of electrical instrumentation failure.

8.2 Types of Control Systems

A control system is the amalgamation of different control schemes applied on the process to control the outputs of the system. These variables can either be temperature, flow or pressure of the system, each controlled by manipulating the input variable of the system. There are two main classifications of the control systems.

8.2.1 Open Loop Control System

An open loop control system does not have the system's output interlinked with the overall control of the system. In an open loop control system, the input variable is monitored and control is applied only on its basis. The disturbances are minimal as no feedback is taken from the output to maintain the system. It is a cost efficient control but the accuracy of the control and effectiveness is very low.

8.2.2 Closed Loop Control System

Closed loop control system uses the feedback from the output stream to take action on the manipulated variable to achieve a certain set point. It has same forward path as open loop system but also has multiple feedback paths to provide information for the desired changes.

The actual process variable conditions are compared with given set point to apply control on the manipulated variable using different variables. A suitable control action is determined on the basis of the error signal generated to bring the system output to the desired value. The accuracy of the closed loop control is far more than the open loop control system and it has more costly maintenance as well.

Instrumentation and process control is a necessity for safe operation of every system, likewise special consideration was given in our project to assess sensitive operations and issue controlling equipment for them. There are two basic parameters that are to be controlled for an operation and they are listed as following:

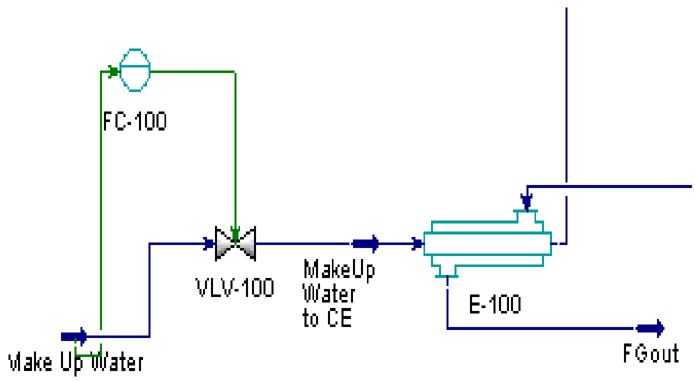
8.3 Installed Controllers

8.3.1 Make-up water flow controller

Flow is necessary to be controlled throughout the operation to increase efficiency and safety of the process. To maintain this flow, we need to control the flow by controlling the input of the overall material balance. The main input of our process is the make-up water. By controlling this flow we can consequently control the overall mass of water in the cycle and capacity of operation. A flow transmitter is placed on the make-up water stream which reads and transmits the value of flow rate at the makeup water stream and manipulates the valve opening to control the flowrate.

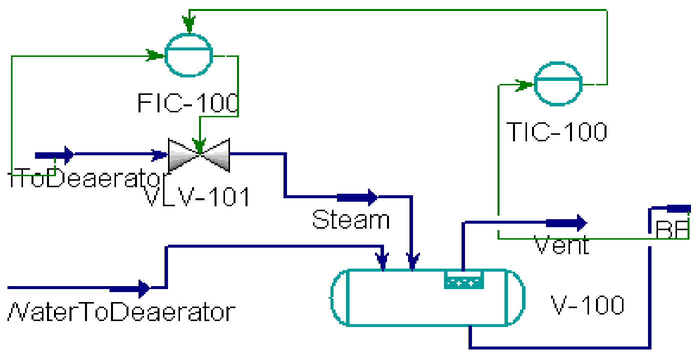
Make Up Water Flow Controller

Make Up Water Flow Controller				
Name of controller	Type of controller	Manipulated variable	Controlled Variable	Action of controller
FC	PID	Valve Opening	Make Up Water Flowrate	Direct



8.3.2 Steam Injection into the Deaerator:

Deaerator				
Name of controller	Type of controller	Manipulated variable	Controlled Variable	Action of controller
FC	PID	Valve Opening	Steam Flowrate	Direct
TC	PID	Steam Injection	Temperature	Reverse



This problem addresses probably the most sensitive parameter of the operation which is the temperature. High temperatures can damage the equipment due to the high kinetic energy molecules contain in high temperature state which in turn can significantly not only damage the equipment but even pose a threat of failure to the whole operation.

To control this feature a temperature transmitter is installed on the deaerator feed stream. As the water is in a cycle throughout the operation, the temperature is required to keep to an optimum. To do this, the temperature transmitter sends output to a flow controller which controls the flow of the steam injection into the deaerator and as the deaerator additionally acts as a heat exchanger. Controlling the steam injection flow can help control the heat exchange and hence temperature of the water in the cycle.

9 Simulation on ASPEN Hysys

The simulation on Aspen Hysys was done to verify material and energy balance calculations along with design parameters. Owing to the complexity of the feed, the system was kept in steady state only.

The components were selected as follows:

Source Databank: HYSYS

Component	Type	Group
CO_2	Pure Component	
CO	Pure Component	
Nitrogen	Pure Component	
Oxygen	Pure Component	
Hydrogen	Pure Component	
Carbon	Pure Component	
H_2O	Pure Component	
SO_2	Pure Component	

Status: OK

Fig 8 a Component List

Peng Robinson was selected as the property package

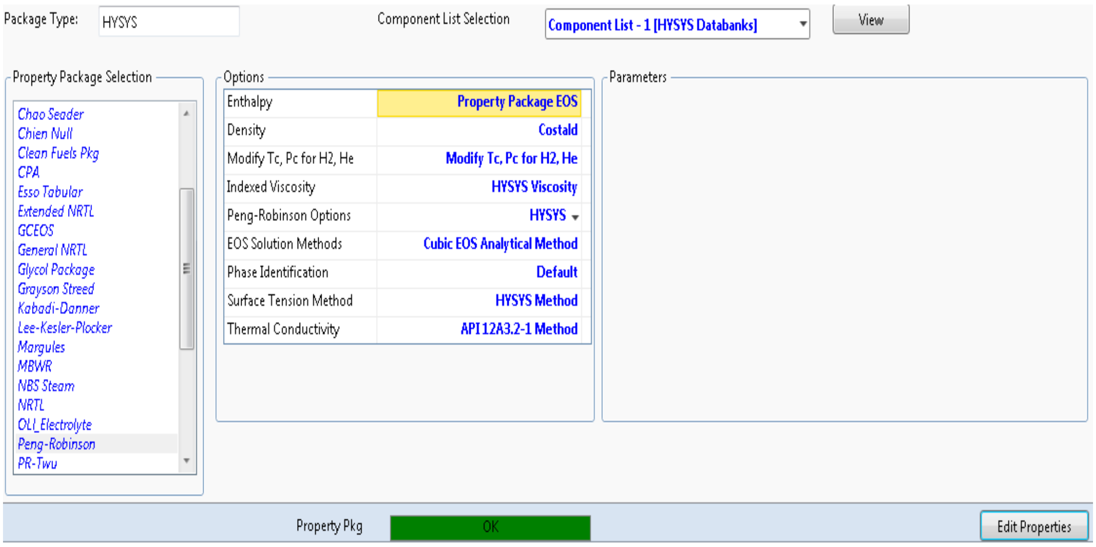


Fig 8 b Property Package

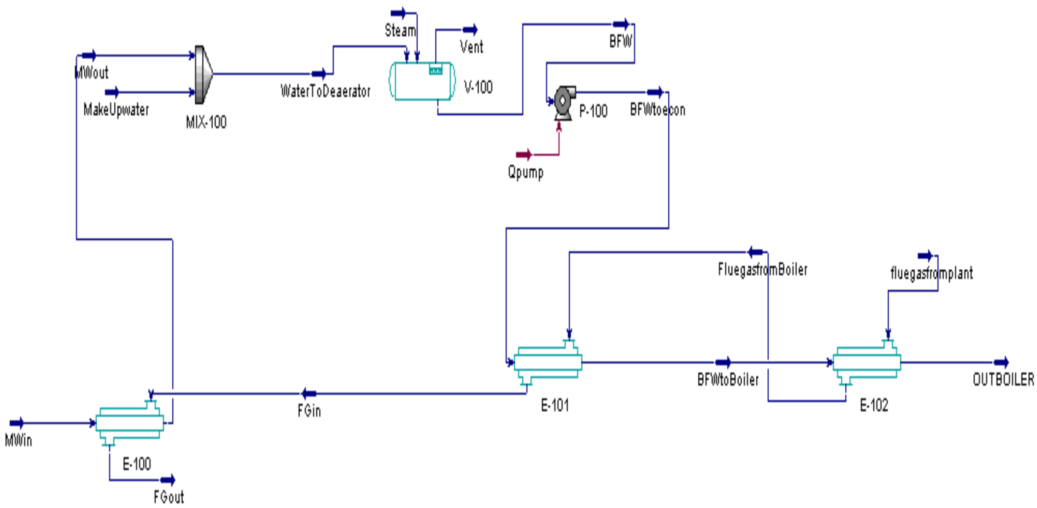


Fig 8 c Aspen Hysys Flow Diagram

10 Materials of Construction

When choosing the material of construction, there are several factors that need to be incorporated. However, the first and foremost aspect is the ability of the material to withstand corrosion, temperature and pressure. The process operates in the harshest of conditions, and is extremely prone to scaling. Here are some of the factors that are kept in consideration:

1. Mechanical properties.
2. Corrosion resistance.
3. Cost.
4. Thermal conductivity

The procedure to determine each of these aspects is:

10.1 Mechanical Properties

The material to be used should undergo testing. Its ability to withstand pressure and temperatures is tested by allowing the material to exist in those conditions.

- The Ultimate Tensile Stress is determined and the proportional limit graph is obtained to determine operating conditions.
- The surface hardness is measured.
- The creep strength of the material is tested.

All these tests were not conducted but data from the literature was helpful in determining the material. The data is summarized in the table below for carbon steel.

Tensile strength, ultimate	**635 MPa**	**92100 psi**
Tensile strength, yield	490 MPa	71100 psi
Modulus of elasticity	0.27-0.30	0.27-0.30
Bulk modulus (typical for steel)	140 GPa	20300 ksi
Shear modulus (typical for steel)	80 GPa	11600 ksi
Poisson ratio (typical for steel)	0.27-0.30	0.27-0.30
Elongation at break (in 50 mm)	10%	10%
Reduction of area	45%	45%
Hardness, Brinell	187	187
Hardness, Knoop (converted from Brinell hardness)	209	209
Hardness, Rockwell B (converted from Brinell hardness)	90	90

Hardness, Rockwell C (converted from Brinell hardness. Value below normal HRC range, for comparison purposes only)	10	10
Hardness, Vickers (converted from Brinell hardness)	196	196
Machinability (based on AISI 1212 steel. as 100 machinability)	60	60

The data is summarized in the table below for Stainless Steel 904L for Condensing Economizer.

Temper	**Annealed**	
Tensile Rm	71	ksi (min)
Tensile Rm	490	MPa (min)
R.p. 0.2% Yield	32	ksi (min)
R.p. 0.2% Yield	220	MPa (min)
Elongation (2" or 4D gl)	35	% (min)

Specific Heat (0-100°C)	**450**	**J.kg-1.°K-1**
Thermal Conductivity	11.5	W.m -1.°K-1
Thermal Expansion	15.8	mm/m/°C
Modulus Elasticity	190	GPa
Electrical Resistivity	9.52	µohm/cm
Density	7.95	g/cm3

10.2 Corrosion resistance

It is not just the pressure and temperature conditions that make it a harsh environment. The surfaces of exchanger are also prone to corrosion.

Stainless Steel 904L is used as a construction material for the condensing economizer. This high alloy stainless steel is added with copper to improve its resistance to strong reducing acids, such as sulphuric acid. The steel is also resistant to stress corrosion cracking and crevice corrosion. Grade 904L is non-magnetic, and offers excellent formability, toughness and weld ability.

10.3 Costing

Material costs play an important role in determining the material. The ideal choice for all the heat exchangers would have been Stainless Steel but that would have multiplied the price to several factors. Therefore, Carbon Steel was used for exchangers where the temperatures were kept above the dew point of Sulfur and SS904L was used for condensing economizer only.

Carbon Steel Cost	**$0.82/kg**
Carbon Steel Max Allowable Stress (σ_d)	0.02 N/mm^2
Stainless Steel Cost	$3.79/kg
Stainless Steel Max Allowable Stress (σ_d)	0.14 N/mm^2

Table 10 a costing parameters

The final cost is calculated using the following equation:

$$\boldsymbol{Cost\ rating} = \frac{\boldsymbol{C \times \rho}}{\boldsymbol{\sigma_d}}$$

10.4 Thermal Conductivity

The system deals with various heat exchangers and condensers so it was necessary to study the thermal conductivity.

Thermal conductivity of Carbon Steel	**36 W/mK at Room Temperature**
Thermal conductivity of SS904L	21.5 W/mK at 500 °C 11.5 W/mK at Room temperature

Table 9 b thermal conductivity

11. HAZOP Study

Health and safety are the essential features of an industry. The government legalities and the health and safety regulations force employers to provide proper health and safety environment to the employees. The health and safety is greatly affected by the hazards that might be present at the workplace. Anything which has the ability to cause the damage is treated as hazard. A hazard is basically a threat which can have the power to cause, financial, physical or chemical damage to a work environment. A strong and vigilant policy needs to be in place in order to overcome this problem of health and safety.

There are many regulations in place for as different health and safety measures. These regulations are implemented in order to enforce the measures that are necessary in a working environment. There could be a variety of hazards and they need to be solved and taken care of, categorically. A detailed HAZOP study can be performed on a specific plant or system to identify the possible hazards and their intensity. The level of risk and the ability of damage for a particular hazard can be evaluated successfully.

The HAZOP Study basically comprises of the following evaluations.

1. Identification of the possible hazards
2. Measures to control for the possible hazards
3. Improvising the process
4. Minimizing the loss due to liability

11.1 Identification:

The most specific and safe way of controlling and rectifying a hazard is first identifying one. There are numerous hazards on our hand in a work field. The experienced personnel and the health and safety officers are placed in order to identify these potential problems and to take best measures for these hazards. We have a process of condensate recovery at our hands and there are numerous hazards that can be related to the process itself.

The first and the foremost is the hazard of burning from the steam. The direct contact of steam to humans can be dangerous and this is treated as the number one hazard for a process involving the condensate recovery. The piping and the equipment that are being employed in the whole process need to be tested and evaluated for the possible hazards. The correct identification is the basic and first step to a safe working environment. The identification can hence identify the possible problem zones and the remedies and measures can be taken on time in order to deal with the hazards.

11.2 Measures

The hazards after identification need a proper channel by the help of which they can be eliminated. Eliminating the hazard is the best solution rather than letting any unwanted scenario to happen and then to control. By controlling the hazards it is ensured that the problem or the incident will not in the very first place. The strategy simply is to avoid any disasters by avoiding any hazards that may be present.

11.3 Improvising

The process that is on hand for the hazard analysis can also be rectified by making some changes. The process is designed in such a way in order to minimize the hazards by effective measures. A control on the hazards offer great control related to health and safety. The different paths which can be hazard for carrying steam from a specific place can be redesigned to go about another route hence by solving the apparent danger of hazards.

11.4 Loss Limitation

The last and the least that could be done is to limit the loss that is expected from a certain hazard. This is the last remedy as this occurs when there is apparently no way of removing the hazard. The hazard is present at the specific place and hence the other measures of catering such a hazardous situation are designed. The limitation of loss is important as this is the last asylum for the minimum loss in the industry.

11.5 Safety of Personnel

The health and safety of the working class is the major concern and the employer is forced for providing the necessary measures in order to minimize the hazards and to provide a safe working environment. The safety of the personnel can be guaranteed by taking certain factors into the account.

First Aid

The most important part while considering the operations and health and safety is providing the first aid in case of any accident. The hazards are considered according to the respective process and equipment. The measures are hence in the light of these two factors. The first aid is the necessary measure that is need to be provided to the workers. The first aid basically aims at the initial health and medical care that is provided to the affecters of an accident. There can be different health hazards that are the prime focus of the provided first aid.

The poisonous gases and the toxic substances are the major concern as these could bring havoc. The other chemical consumptions and effeteness is also taken care of properly. The workers that exposed to high temperatures and gases also need to have periodic checkups that can ensure the prevention of any prolonged disease.

Protective Equipment

The first line of defense for any worker is the PPE that is assigned to him. The personal protective equipment are the insurance of a worker and it solely is the barrier between the exposed worker and the hazard. There are numerous equipment that are employed as PPE and the selection of these is dependent on the nature of process.

The important PPEs include the protection for head and eyes. The head is a vital part and the most exposed one. The safety helmets and the safety goggles are used for protection. The respiratory and skin protection is also of pioneer importance. The respiratory masks and the synthetic suits are used for complying with the hazards associated with skin, body and respiration.

Regulations and Training

The regulations and laws that are followed for health and safety also hold key importance in industry. The laws are illustrated in front of the workers and the importance and need of these regulations is shown in order to assist them to follow the rules and regulations. The regulations and the safety measures could make a difference of life and death on the table of a busy industry.

The training of the personnel is also important as this would lead to more experienced and effective workforce. The training is also important as the plant can have some delicate and hazardous places which can be visited only by the experience professionals. The different important PPEs that are necessary for entering a specific part of plant is also important.

The tanks and open vessels can only be visited after some precautionary measures. The tanks is first washed with water or purged with nitrogen. The written permission is necessary for visiting these places. The gas test needs to be performed. These are the important measures that are necessary before the tank or the vessel is visited by the personnel.

11.6 Outcome of HAZOP Study

The HAZOP study can have great impact on the design project. There are different insights that can be enlightened by the help of the hazard study. The team that is in the supervision of the HAZOP study has the technical insights. The possible measures that are needed in order to minimize the hazards. The technical knowledge and visualization can help to identify the causes and the consequences related to a specific hazard. HAZOP study is comprehensive and has the potential to comply with the hazards that are present at the plant.

There are several points that are to be tested for the hazard study. The complete guide would results in a safe and accurate HAZOP study.

1. Intentions

The intentions are the expectations according to which the plant has to operate. The operation is expected to free from any variance or deviations with respect to the study notes. There can be diagrammatic or descriptive forms for the intentions part of the HAZOP study.

2. Deviations

These are the variances that are encountered in the intentions. They can be evaluated by using the use of the guide words. The guide words need to be applied systematically for the correct evaluation.

3. Causes

These are basically the problems due to which the deviations exist. The deviations can be identified correctly and then the origin of the problem can be easily traced. The original problem can have different cause. The causes can be human error, systematic error, disruptions, unexpected scenarios and loss of power.

4. Consequences

These are the results that occur because of the problems that exist in system. These results can be in the form of any unwanted circumstances. The eruption of any vessel, fire or release of toxic chemicals.

5. Guide Words

The guide lines on the basis of which the problem of deviations can be evaluated. The list of the guide words help to make the assessment on the different stages of the process plant. The different teams working in different areas of the project have their own specific guide words on the basis of which the HAZOP study is carried out.

Types of HAZOP

Process HAZOP is carried out in order to identify the problems and deviations that might exist in the operational sequence of a plant.

Software HAZOP is performed on different programmable logic devices, and the general software employed in the working of the plant or system

Human HAZOP is a group of HAZOP studies that aim on the mistakes that lead to the technical failures associated with human error.

11.6.1 Procedure for HAZOP Study

The HAZOP study holds its importance in the industry. There is however a brief and elaborative way of performing the HAZOP study. The following steps can be taken in order to successfully evaluate the HAZOP study.

- Division of the system into different sections
- Choosing the basis as study notes
- Depicting the intention of the section
- Selecting the involved parameters
- Applying the guide word
- Determination of causes of deviation
- Evaluating the consequences
- Recommendations
- Recording the information

11.7 Equipment

11.7.1 Deaerator

Guide word	Deviation	Cause	Consequence	Safeguard
More	Temperature	Higher flow of steam	Might damage insulation Overheating of column	Temperature regulation and control.
Low	Temperature	Low pressure steam. Leakage of steam	Inefficient removal of oxygen	Temperature regulation and control.
Low	Flow	Pump blockage Major leak in pipeline	Overheating of column	Flow control and regulation
More	Flow	Problems with upstream control valves	Accumulation of water in deaerator	Flow control and regulation
Low	Pressure	Upstream pressure variations Upstream leakage	Saturation temperature decline	Pressure regulation and control
More	Pressure	Upstream Pressure variation	Saturation temperature elevation More load on deaerator	Pressure regulation and control

11.7.2 Waste Heat Recovery Boiler

Guide Word	Deviation	Cause	Consequences	Safeguard
More	Pressure	Upstream pressure variations.	Boiling point elevation.	Pressure regulation and control.
Low	Pressure	Leakages upstream or within the boiler. Upstream pressure variations.	Less steam generated	Pressure regulation and control.
More	Temperature	High flow rate of Exhaust gases Upstream process deviations.	High volumes of steam generated. Higher steam temperature. Damage to pipes and tubes from high temperature	Temperature regulation and control.
Low	Temperature	Low flow rate of exhaust gases Upstream process deviations. Leakage.	Poor steam generation. Lower steam temperature.	Temperature regulation and control.
More	Flow	Problems with Boiler feed water pump. Problems with upstream control valves.	More load on boiler tubes. More need for steam. Accumulation of water in boiler	Flow regulation and control.

11.7.3 Condensing Economizer

Guide word	Deviation	Cause	Consequence	Safeguard
More	Temperature	Boiler Economizer failure Fouling in boiler or economizer tubes	Higher temperature of make-up water damage to insulation more water vapor condensed	Temperature regulation and control
Low	Temperature	Improper insulation Faulty instrumentation and control	Less water vapor condensed Lower temperature of make-up water	Temperature regulation and control
Low	flow	Pump blockage Major leak in pipeline	Inefficient heating of make-up water	Flow regulation and control
More	Flow	Control valve failure	More load on economizer tubes	Flow regulation and control
Low	Pressure	Leakages upstream or within the condensing economizer. Upstream pressure variations	Less water vapor condensed	Pressure regulation and control
More	Pressure	Upstream pressure variations. .	More water vapor condensed	Pressure regulation and control

11.7.4Boiler Feed Water Pump

Guide Word	Process Parameter	Cause	Consequences	Safeguard
More	Pressure	Increased pressure of deaerator	Pump damage. Recirculation or backflow.	Flow regulation and control.
Low		Decreased pressure of deaerator	More pump power. Cavitation in pump.	Flow regulation and control.
More	Flow	Increased output from deaerator Increased level of deaerator	Decrease in pump head. Reduced pump efficiency. Increased NPSH.	Flow regulation and control.
Low		Decreased level of deaerator Decreased output from deaerator.	Reduced pump efficiency. Chances of cavitation. Chances of recirculation.	Flow regulation and control.

12 Conclusions

By installing a condensing economizer, the steam demand has reduced from 360.39 kg/hr to 234.69 kg/hr. The steam saved is 125.70 kg/hr. In doing so, more steam goes to the plant eventually reducing the load on the process boilers.

The makeup water instead of going directly to the deaerator goes to the economizer where it is preheated. This preheated make up water reduces the steam demand as well as the required boiler feed water to generate 4000kg/hr of steam. Less amount of BFW is used to generate same amount of steam.

Comparing the energy balance for both the fuels, the flue gas of Natural gas is seen to be more efficient for the same change in temperature as compared to that of HFO.

Natural Gas meets the required goal at lower supply volumes and has a less costly stack.

13 References:

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