

Design of a Flue Gas Condenser



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Dedication

This project and report is dedicated to our teachers, parents and friends; whose constant help and encouragement made it possible for us to complete this project successfully.

Acknowledgements

We have taken efforts in this project. However, it would not have been possible without the support and assistance of a many notable people.

We are thankful to Dr. Muhammad Bilal Khan Niazi for being the idyllic supervisor. His guidance and constant, unwavering support helped us complete the project on time. He clarified the objectives and made sure that we did not go astray from the desired aims of the project. He was there to help us prepare presentations and did his best to identify any flaws that could question the credibility of the project.

Further, Mr. Mohammad Mirza Nabeel, our industrial supervisor, provided us with all the necessary information and data needed to complete the project. He informed us of the important aspects that needed to be considered for the design of equipment.

Our department, School of Chemical and Materials Engineering, NUST also deserves acknowledgement for providing us with an innovative and professionally sound environment to encourage execution of such projects.

Finally, we also owe a great deal to our parents and colleagues, who kept us motivated at each step along the project execution.

Certificate

This is to certify that this work is the result of research carried out by **Ms. Fatima Rizwan, Mr. Muhammad Muzammil and Ms. Aqsa Afzal**, under the supervision of Dr. Muhammad Bilal Khan Niazi of Chemical Department in School of Chemical and Materials Engineering, NUST, H-12, Islamabad, Pakistan.

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Nomenclature

π	Pi
\dot{m}	Mass flowrate
T_1	Hot fluid inlet
T_2	Hot fluid outlet
t_1	Cold fluid inlet
t_2	Cold fluid outlet
\dot{Q}	Heat transfer rate
U	Overall heat transfer coefficient
A	Area
$LMTD$	Logarithmic mean temperature difference
F_t	Temperature correction factor
d_{to}	Tube outer diameter
d_{tw}	Tube wall diameter
d_{ti}	Tube inner diameter
D_s	Shell diameter
d_e	Wetted parameter
L	Length
N_t	Number of tubes
Re	Reynolds Number
Nu	Nusselt Number
Pr	Prandtl Number
c_p	Specific heat capacity
k	Thermal conductivity
μ	Dynamic viscosity

μ_w	Dynamic viscosity at walls
G	Mass flux
ρ	Density
P	Pressure
u	Velocity
N_p	<i>Number of tube passes</i>
<i>WRSB</i>	<i>Waste Recovery Steam Boiler</i>
<i>WRSG</i>	<i>Waste Recovery Steam Generator</i>
<i>HFO</i>	<i>Heavy Fuel Oil</i>
<i>SCC</i>	<i>Stress Corrosion Cracking</i>

Abstract

Acid rain, caused by sulphur oxides in the atmosphere, and global warming, caused by high temperature emission and presence of various other oxides in the flue gases, is two of the many problems faced today. Engro Foods plans on reducing these two phenomena by installing a flue gas condenser. This condenser will condense out the acids and simultaneously, reduce the temperature of the flue gas, contributing to relatively more environment friendly discharge. To achieve our purpose the flue gas is passed through several equipment for heat exchange and energy recovery as well as the some of the constituent components are converted and recovered in the form of useful components. A heat exchanger will be designed to bring down the flue gas to first, its acid dew point and then, to further reduce the temperature. The energy recovered is utilized for heating the water for steam generation, while the acids form during the condensation process neutralize the basic water coming out as by-product of dairy products manufacturing.

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1. Introduction

In the last decade, large thermal power plants were forced to build and improve their flue gas treatment systems, because many countries in the developed world had passed legislation dictating the level of emissions that a polluter must not exceed in order to be able to operate in the future. The systems for flue gas treatment in thermal power plants are intended to lower acid and dust components in order to maintain the health of the environment to the greatest extent possible,

Three types of fuels are being burnt separately in the power house and flue gas comes out at the end of gas turbine and is further sent to the heat exchanging assembly for recovering useful amount of energy and condensing out some useful components.

Heavy fuel oil, diesel and natural gas are being burnt in three separate power houses and flue gas is released from the gas turbine. It contains large amount of useful energy and various components in variable quantities. This flue gas if sent to the environment without any further treatment will result in a loss of valuable energy and all the materials will be discharged into the environment, causing safety risks and environmental and economic setback.

To decrease the loss, this flue gas is passed through several stages for thermal and material recovery, increasing the efficiency and economical value of the project.

The gas is being passed through waste recovery steam generator (WRSG); that mainly comprises of two parts; a waste recovery steam boiler (WRSB) and an economizer. This causes a sufficient decrease in the temperature of flue gas but the flue gas coming out of WRSG still contains valuable amount of energy and since in the WRSG only heat transfer phenomena is occurring, the flue gas composition is still intact and contains components that's could be utilized in the processes.

In the condenser, alongside with heat transfer, phenomena of mass transfer occur simultaneously. The condenser is an indirect type heat exchanger, where the flue gas is in the tube section while the cooling water is in the shell side.

Since flue gas contains various components, a few of which upon oxidation could cause problems like corrosion, erosion and material damage. But if discharged into the atmosphere, they could cause severe environmental pollution and acute health issues. And upon heat exchange, the temperature of the flue gas is lowered to the point where the temperature is decreased below the Acid dew point of sulfuric acid.

Sulfur dioxide is formed as a result of combustion of sulfur and in the oxidizing environment, some of it is further converted to sulfur trioxide. The water vapors condensed upon heat exchange come in contact with the sulfur trioxide and form sulfurous and sulfuric acid. Since no other compounds are condensed at this temperature, the sulfur acids formed are impurity free and highly concentrated. This contributes to the material recovery and provides useful acid that is further utilized for the neutralization of basic water coming out as the dairy and food industrial processes waste water. This waste water, after treatment with acids is discharged into the environment as clean neutral water.

It is known commonly that sulfur dioxide and sulfur trioxide emissions from the plants are a major reason for acid rain and sites are assigned to control monitor or such emissions. Problems related to emission of sulfur trioxide and sulfuric acid are not much widely recognized. There is also less awareness about the maintenance problems that arise due to presence of sulfuric acid in stack gases.

Corrosion failures due to condensation of flue gases containing SO_3 , H_2O and NO_x still occur more frequently than expected. Several types of failures occur like; general corrosion, stress corrosion cracking (SCC) and pitting attack. Combustion product acidic gases are a major cause of rapid corrosion when condensed in energy-recovery system or on pollution control.

For avoiding the material damage problem, two main things are to be considered while selecting the suitable material; that the material could withstand high temperatures and oxidizing conditions. Low carbon content eradicates the risk of inter-crystalline corrosion and high austenitic structure of the material imparts high toughness. Chromium imparts corrosion resistance properties and hence increases its utility and durability in highly corrosive/oxidizing environment.

2. Literature Review

2.1 Acid Dew Point

Acid dew point at a given pressure refers to the temperature of a flue gas (product gas after combustion), when any gaseous acid present in the flue gas starts condensing to liquid acid.

It refers to a point where the flue gas is saturated with the gaseous acid; no further gaseous acid can be held by the flue gas.

Most of the industries involving combustion processes, recover heat energy from the flue gas before emitting it to the atmosphere from the stack gas. The gas is cooled to the temperature below the acid dew point, because upon further condensation, at the acid dew point the liquid acid forms and creates severe corrosion problems to the equipment used for cooling, emitting and transporting the flue gas.

Acid dew point for a flue gas is dependent on the composition of fuel being burnt and composition of the resultant flue gas. It impacts on the process equipment life. The plant area, where knowing the acid dew point is critical is point where the gas has to be cooled to temperature near or below its acid dew point. Once known, it enables the acid plant to recover maximum amount of heat energy in heat recovery system by cooling the gas close to its dew point. It enables the plant to work at maximum thermal efficiency.

2.2 Sulfuric Acid Dew Point

When the flue gas is cooled to a sufficient low temperature, condensation occur and liquid appears on the surface when the temperature is decreased beyond dew point. This liquid phases is mainly sulfuric acid, which is a highly corrosive compound, causes acid corrosion, also known as low temperature corrosion.

The presence of sulfuric acid in gaseous form, results in increase in the sulfuric acid dew point of flue gas as compared to water dew point of the flue gases. The change is quiet high for even minute quantity of acid present.

The amount of moisture present has a direct relation with acid dew point temperature for given concentration of sulfur trioxide .The maximum obtainable moisture content in a flue gas is determined by the moisture content of combustion air and the moisture content along with hydrogen content of the fuel. This is determined by operational parameters and ultimate analysis of fuel. The quantity of gaseous sulfur trioxide (SO₃) and water vapor (H₂O) present in flue gas impose a great effect on the acid dew point of sulfuric acid for the flue gas. The following relationships have been derived to calculate the acid dew point.

Verhoff/Banchero (1974)^[1]

$$T_D = \frac{10000}{15.13 - 0.2943 \times \ln(p_{H_2O}) - 0.858 \times \ln(C \times p_{SO_2}) + 0.062 \times \{6.633 - \ln(C \times p_{SO_2})\} \{6.633 - \ln(p_{H_2O})\}}$$

Hasse / Borgmann (1981)^[2]

$$t_D = [255 + 27.6 \times \log_{10}(p_{H_2O}) + 18.7 \times \log_{10}(C \times p_{SO_2})]$$

Neubauer (1962)^[7]

$$t_D = t_S + (290.54 - 30.79 p_{H_2O}) p_{SO_2}^{(0.0959 + 0.1430 p_{H_2O} - 0.1669 p_{H_2O}^2)}$$

Ohtsuka (1961)

$$t_D = 20 \lg V + A$$

Pierce (1977) / Mueller (1959) / Okkes (1987)

$$t_D = 203.5 + 27.6 \log_{10}(p_{H_2O}) + 10.83 \log_{10}(C \times p_{SO_2}) + 1.06 \{ \log_{10}(C \times p_{SO_2}) \}^{2.19}$$

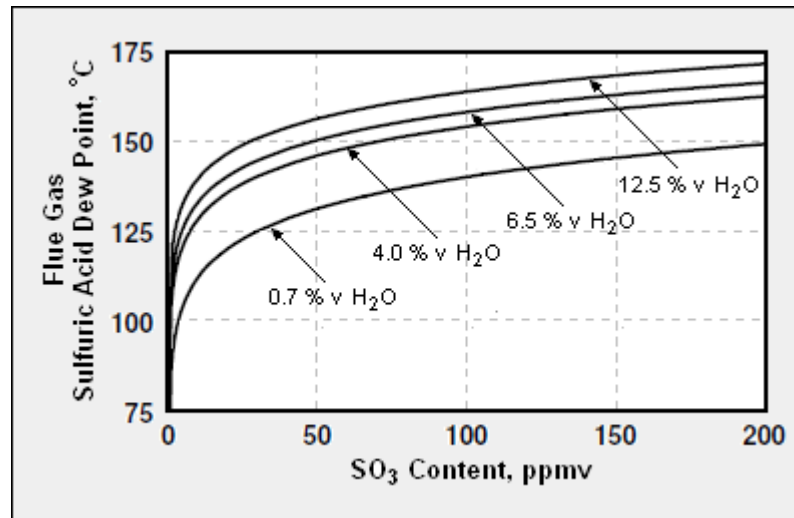


Figure 1: Sulfuric acid dew points of typical combustion flue gases, as a function of sulphur trioxide content, and water vapour

The acid dew point of a flue gas can be predicted fairly closely, if its composition is known. This prediction of sulfuric acid dew point of flue gas is necessary to mitigate corrosion related problems in heat exchanging systems and process equipment. The flue gas coming out of a combustion process in thermal power plant has usually sulfuric acid dew point in range of about 120 °C to 150 °C (250 - 300 °F).

2.3 Flue Gas

Flue gas is the gaseous state exit product of a combustion process. Flue gas coming out of the combustion facilities are a major source of environmental pollution. It is steered to flue gas ducts and is directly released into the atmosphere.

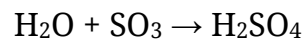
Conventionally, the flue gas comes out of the power plant at very high temperature and this is reduced by passing through a water pre-heater where the sensible heat of the flue gas is utilized to pre-heat water or combustion air. This leads to a significant increase in the boiler efficiency.

Flue gas coming out of combustion process of burning fuels (coal, natural gas, biomass or fuel oil) is composed primarily of carbon dioxide (CO₂)

and water vapor (H₂O) in addition, some amount of gaseous nitrogen along with unburnt (excess) oxygen remaining from the incoming air for combustion. The composition flue gas depends upon the composition of fuel being burnt and amount of air supply.

In addition, it also contains minute quantities of particulate matter, nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur oxides as gaseous sulfur dioxide (SO₂) and sulfur trioxide (SO₃). SO₂ forms as a result of combustion of sulfur present in the fuel and upon oxidation, some of it is converted to SO₃. This further reacts with the water vapor formed upon condensation and is converted to sulfuric acid (H₂SO₄).

The reaction occurring is as follow



Water + Sulfur Trioxide → Sulfuric Acid

From the literature it is deducted that almost all of the sulfur trioxide is converted to sulfuric acid. Therefore, only sulfuric acid is present in the flue gas near the acid dew point and amount of sulfur trioxide left is negligible. However, sulfur dioxide starts to combine with condensed water vapors only when the flue gas temperature is reduced to the dew point of water vapor.

2.4 Condensation

Condensation is a heat transfer process, in which a gaseous substance is cooled and converted to liquid state. It is the process of deposition of a solid or liquid from its vapor state upon a surface that is relatively cooler than the adjacent gas. It is the reverse process of vaporization.

Condensation of a substance occurs when the pressure exerted by its vapors is greater than the vapor pressure of the solid or liquid phase of the substance at the temperature of surface upon which the condensation process is happening.

It occurs when the dew point temperature of the substance is reached or crossed. It occurs when the vapor is cooled to its saturation limit, the molecular density on the gaseous phase reaches its maximum threshold.

2.4.1 Types of Condensation

2.4.1.1 Surface Condensation

Surface condensation occurs when vapors come in contact with a surface that has a temperature lesser than their saturation temperature. The liquid can form in two ways over the surface:

Drop-wise Condensation

As liquid condenses out of the vapors on the cooler surface, it tends to form droplets on the surface. This happens when the cool surface is coated with a material that is wetness proof. Hence, drop-wise condensation has a high heat transfer coefficient, however, they aren't used in industries due to unavailability or expense of such materials.

Film-wise Condensation

Liquids, form a film on the cooling surface. This film covers the entire contact area, hence reducing the heat transfer coefficient sufficiently.

2.4.1.2 Bulk Condensation

Bulk condensation occurs in the entire mass of the vapors. The liquid droplets are suspended in the vapors.

2.5 Predicting the SO₃ Content of Flue Gases

SO₃ if present in the stack gas could lead to undesirable consequences. It forms sulfuric acid upon contact with water and sulfuric acid condenses at temperature below 100°C. If temperature of the flue gas falls below the sulfuric acid dew point, formation of sulfuric acid aerosol occurs, forming a film of sulfuric acid that is deposited on any surface exposed, at temperature less than dew point.

From the above mentioned equation for calculation of the sulfuric acid dew point of a flue gas, it is clear that partial pressure of sulfur trioxide present in flue gas is needed. The partial pressure could be easily determined if the volume percent of sulfur trioxide in the flue gas and total pressure of the flue gas is given. Since, partial pressure for the components of a gaseous mixture could be found by simple multiplication of volume fraction of the component in the gaseous mixture by the total pressure exerted by the gas.

It is quite difficult to directly determine the accurate volume percentage of sulfur trioxide present in a flue gas using theoretical calculations. However, this is done indirectly by using the volume percent of sulfur dioxide in the flue gas as it could be easily determined by using conventional assumption that around 90 percent or more of the sulfur present in the fuel is oxidized upon combustion and converted to gaseous sulfur dioxide. Another common assumption is that about 1-5 percent of this sulfur dioxide upon further oxidization is converted to sulfur trioxide. Thus by knowing the volume percent and partial pressure of sulfur dioxide in the flue gas, the amount of sulfur trioxide formed and its partial pressure can be predicted. This will ultimately help in determining the acid dew point of the gas.

Sulfuric acid concentration is dependent on the SO_2 to SO_3 conversion rate along with the surface temperature of the condenser wall. . Thus, controlling the SO_3 content is important along with the temperature to control and determine the amount of sulfuric acid produced. It is also dependent upon variables including; gas residence time, excess air level, concentration of sulfur dioxide and presence of catalyst.

3. Process Description

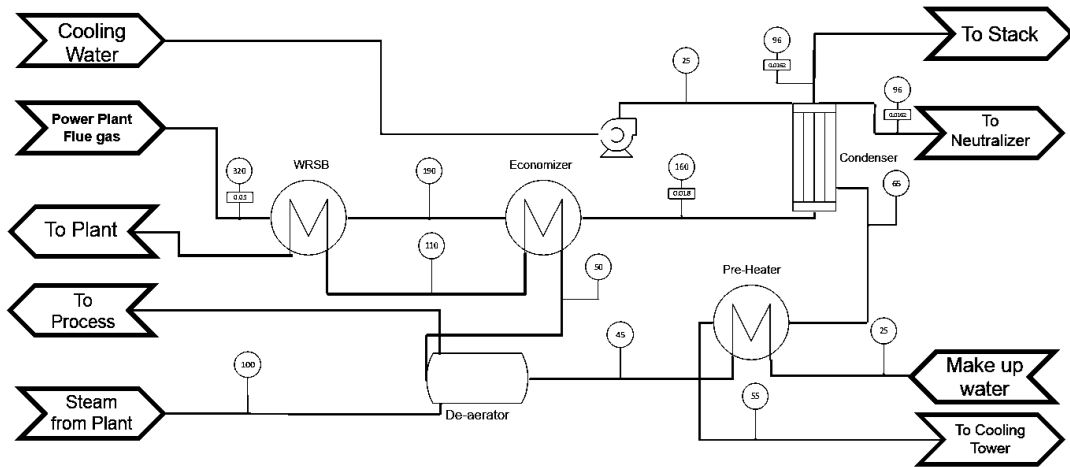


Figure 2: Process flow diagram downstream to the power plant

3.1 Power Plant

The power plant burns fuel to generate power for the plant. The fuels differ for each of the plant. The three fuels are, heavy fuel oil (HFO), natural gas and diesel. The exhaust gas from the turbines is sent to the waste recovery steam boiler.

3.2 Waster Recovery Steam Boiler

In the waster recovery steam boiler, the steam loses heat to generate steam. Power plant burns the fuels, to run the gas turbine. The exhaust gas is sent to the WRSB where its temperature is dropped to 190 °C. Counter-currently, water is present in tubes, which forms wet steam. The water runs in tube, while the flue gas is in the shell side.

3.3 Economizer

The flue gas next goes into the economizer. Here, the flue gas heats boiler feed water, and so it acts like a pre-heater to the boiler. The purpose of economizer is to reduce energy required by the boiler to generate steam and increase efficiency, as the water is at a higher temperature now. Currently, the gas is exhausted at this point, at a temperature of 190 °C.

3.4 Condenser

A condenser will be placed at the downstream of the economizer. The condenser will cool the flue gas, down to its acid dew point, then further to 96 °C. At the acid dew point, sulphur oxides will react with water and form acid. This acid is collected separately and sent to waste water treatment plant for neutralization of waste water. The flue gas, now free of acids and at a lower temperature, the gas will be exhausted. Cooling agent in the condenser is the water from cooling towers.

3.5 Pump

The water for the condenser comes directly from the cooling tower. The water is at 1 atmospheric pressure. Since significant pressure drops occur in the condenser and the pre-heater, a pump is installed upstream to the condenser.

3.6 Pre-heater

A pre-heater will be used to extract the heat from the water coming from the condenser. The pre-heater will heat the boiler makeup water, raising its temperature from 25°C to 45°C. Meanwhile the hot water is cooled from 65°C to 55°C.

3.7 De-aerator

A de-aerator is used to remove any dissolved air from the boiler-feed water. Presence of dissolved air in the boiler feed water can lead to corrosion in the boiler. To prevent this, oxygen is removed by mechanical method. High pressure steam is passed in cross-flow to the boiler feed water. The steam takes the air out with it.

4. Material and Energy Balance

4.1 Fuel Composition

Element Composition (wt. %)	Fuel		
	HFO	Diesel	Natural Gas
C	85.1	85.7	72.5
H	10.9	13.4	23.4
S	4.0	0.9	4.08×10^{-4}
O ₂	Nil	Nil	1.09
N ₂	Nil	Nil	3

Table 1: Fuel composition

4.2 Flue Gas Composition

Compositions (wt.%)	Flue Gas Origin		
	HFO	Diesel	Natural Gas
CO ₂	5.12	4.74	8.61
CO	0.01	0.01	0.01
H ₂ O	3.22	3.63	6.35
SO ₂	0.12	0.02	4.17×10^{-5}
SO ₃	0.02	0.00	5.80×10^{-6}
O ₂	1.09	1.08	2.50
N ₂	56.44	54.86	63.53
NO	0.01	0.01	0.08
Unburnt fuel	33.99	35.64	18.92

Table 2: Flue gas composition

4.3 Flue Gas Properties Table

	Flue Gas Origin		
	HFO	DIESEL	NATURAL GAS
Total Mass Flow of flue gas (kg/s)	16.00	16.00	16.00
Acid Dew Point of Flue gas (°C)	143.90	132.67	105.00
Temperature at power plant outlet (°C)	320	400	510

Table 3: Flue gas properties

4.4 Material and Energy Balances

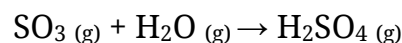
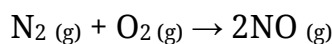
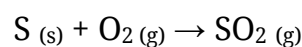
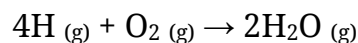
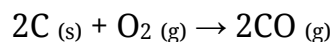
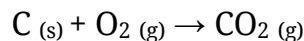
4.4.1 Formula Used in Material Balance

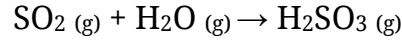
The fuel entering the power plant is burnt with excess air and the flue gas is the end product along with energy.

Composition is given in weight percentage. In order to do the calculations it is converted to moles, using basic conversion

$$n = \frac{w}{Mr}$$

Now using the stoichiometry for combustion reaction, we calculated the amount of air utilized and the excess oxygen supplied. The reactions occurring are as stated





Amount of oxygen required is calculated using stoichiometric equations

$$n_{O_2 Total} = n_{O_2 required} + n_{O_2 excess}$$

$$n_{air supplied} = n_{O_2 Total} \times \frac{100}{21}$$

$$n_{N_2} = n_{air supplied} \times \frac{79}{100}$$

According to the data provided, the efficiency of combustion process is 35%; implying that the conversion of fuel is also 35%.

$$n_{CO_2 prod} = n_C \times \eta_{comb}$$

$$m_{CO_2 prod} = n_{CO_2} \times Mw_{CO_2}$$

Similarly, the moles and mass of water is calculated.

For the amount of sulfur dioxide produced, it is assumed that 90% of sulfur is converted to sulfur dioxide while the rest of 10% undergoes further oxidation and is converted to sulfur trioxide.

$$n_{SO_2 prod} = n_S \times \eta_{comb} \times 0.9$$

$$m_{SO_2 prod} = n_S \times Mw_{SO_2}$$

$$n_{SO_3 prod} = n_S \times \eta_{comb} \times 0.1$$

$$m_{SO_3 prod} = n_S \times Mw_{SO_3}$$

Nitrogen is usually inert, but in the given oxidizing conditions 25% of nitrogen supplied undergoes conversion, while the rest stays intact

$$n_{NO produced} = n_{N_2} \times 2 \times 0.25$$

$$m_{NO produced} = m_{NO} \times n_{NO} = n_{N_2} \times Mw_{NO}$$

Since all of the sulfur trioxide produced is completely converted to sulfuric acid

$$m_{H_2SO_4 produced} = \left(\frac{m_{SO_3}}{Mw_{SO_3}} \right) \times Mw_{H_2SO_4}$$

$$m_{H_2SO_3 \text{ produced}} = \left(\frac{m_{SO_2}}{MW_{SO_2}} \right) \times MW_{H_2SO_3}$$

65% of the fuel is left as combustion process is 35% efficient only. This unburnt fuel is primarily composed of Carbon and hydrogen along with traceable amounts of other substances.

$$n_{Unburnt} = (n_{Total C} + n_{Total H}) \times 0.65$$

The given mass flow rate of flue gas is 16 kg/s.

We performed the calculations considering 100 kg/s of fuel gas.

$$\text{weight \%} = \frac{m_{comp}}{\text{Mass of fuel}} \times 100$$

Now for the composition of 16kg/s, we perform simple calculation

$$\text{weight \%} = \frac{m_{comp}}{16} \times 100$$

In the WRSG, the simple heat transfer is happening and no material transition occurs. Single input stream enters and leaves as a single output stream with the same composition as inlet.

While in condenser, the single inlet stream comes out as two output streams, one is the stack gases that are exited from the top while the acids are collected from the bottom in liquid state.

$$\dot{m}_{in} = \dot{m}_{out}$$

$$\text{Flue gas in} = \text{Stack gases} + \text{condensate}$$

$$\text{Flue gas} = CO_2 + CO + NO + H_2O_{(vap)} + O_2 + N_2 + \text{Unburnt fuel} + H_2SO_4 + H_2SO_3$$

4.4.2 Formula Used in Energy Balance

For a closed system, where the heat transferred by one stream is the heat gained by the other stream, the energy content is calculated using the following equation.

$$Q = m \times c_p \times \Delta T$$

$$\dot{Q}_{in} = \dot{Q}_{out}$$

$$\dot{m}_{hot} \times c_{p_{hot}} \times (T_{hot} - T_{ref}) = \dot{m}_{cold} \times c_{p_{cold}} \times (T_{cold} - T_{ref})$$

This heat capacity value is calculated using the formula,

$$c_p = a + b \times T + c \times T^2 + d \times T^3$$

$$\Delta H = H_{out} - H_{in}$$

When upon the heat transfer, the phase change occur, we take in account the latent heat for the phase change and the equation becomes,

$$Q = m(c_p \times \Delta T - l_v)$$

4.4.2 Material and Energy Balance Downstream to HFO Power Plant

WRSB

	Inlet (kg/s)	Outlet (kg/s)
Hot Side		
	Flue gas	Flue gas
CO₂	0.819	0.819
CO	0.002	0.002
H₂O	0.509	0.509
H₂SO₃	0.024	0.024
H₂SO₄	0.003	0.003
O₂	0.174	0.174
N₂	9.030	9.030
NO	0.001	0.001
Unburnt Fuel	5.438	5.438
Total	16.00	16.00
Cold Side		
Steam Produced	2.762	2.762

Table 4: Material balance on WRSB

	Inlet	Outlet
	Hot Side	
Temperature (°C)	320.00	190.00
Flue Gas Enthalpy (kW)	7386.08	3985.47
Heat Lost (kW)	3400.62	
	Cold Side	
Temperature (°C)	110.00	188.40
Steam Enthalpy (kW)	983.13	4382.96
Heat Gained (kW)	3399.83	
Losses (kW)	0.79	

Table 5: Energy balance on WRSB

Economizer

	Inlet (kg/s)	Outlet (kg/s)
	Hot Side	
	Flue gas	Flue gas
CO₂	0.819	0.819
CO	0.002	0.002
H₂O	0.509	0.509
H₂SO₃	0.024	0.024
H₂SO₄	0.003	0.003
O₂	0.174	0.174
N₂	9.030	9.030
NO	0.001	0.001
Unburnt Fuel	5.438	5.438
Total	16.00	16.00
	Cold Side	
Boiler Feed Water	2.762	2.762

Table 6: Material balance on economizer

	Inlet	Outlet
	Hot Side	
Temperature (°C)	190.00	160.00
Flue Gas Enthalpy (kW)	3985.47	3234.06
Heat Lost (kW)	751.40	
	Cold Side	
Temperature (°C)	45.03	110.00
BFW Enthalpy (kW)	231.72	983.13
Heat Gained (kW)	751.40	

Table 7: Energy balance on economizer

Condenser

	Inlet (kg/s)	Outlet (kg/s)	
		Hot side	
		Flue gas	Flue gas
			Condensate
CO₂	0.819	0.819	
CO	0.002	0.002	
H₂O	0.509	0.509	
H₂SO₃	0.024		0.024
H₂SO₄	0.003		0.003
O₂	0.174	0.174	
N₂	9.030	9.030	
NO	0.001	0.001	
C	5.438	5.438	
Total	16.00	16.00	
		Cold side	
Cooling Water	10.619	10.619	

Table 8: Material balance on condenser

	Inlet	Outlet
	Hot side	
Temperature (°C)	160.00	96.00
Flue Gas Enthalpy (kW)	3234.06	1455.61
Condensate	-	-19.63
Heat Lost (kW)	1778.45	
	Cold side	
Temperature (°C)	25.00	65.00
Cooling Water Enthalpy (kW)	0.00	1778.45
Heat Gained (kW)	1778.45	

Table 9: Energy balance on condenser

Pre-Heater

	Inlet (kg/s)	Outlet (kg/s)
	Hot Side	
Cooling Water	10.619	10.619
	Cold Side	
Make up water	5.309	5.309

Table 10: Material balance on pre-heater

	Inlet	Outlet
	Hot Side	
Temperature (°C)	65.00	55.00
Cooling water Enthalpy (kW)	1778.45	1333.84
Heat Lost (kW)	444.61	
	Cold Side	
Temperature (°C)	25.00	45.00
Make up Water Enthalpy (kW)	0.00	444.61
Heat Gained (kW)	444.61	

Table 11: Energy balance on pre-heater

De-Aerator

Inlet (kg/s)		Outlet (kg/s)	
Make up water	5.309	BFW	2.762
Condensate Steam	0.010	Plant water	2.547
Total	5.319	Purge	0.010
		Total	2.772

Table 12: Material balance on de-aerator

Inlet (kW)		Outlet (kW)	
Make up water	444.61	BFW	231.72
Condensate Steam	1.53	Re-Use	212.89
Total	446.15	Purge	1.53
		Total	446.15

Table 13: Energy balance on de-aerator

Pump

	Inlet	Outlet
Water (kg/s)	10.62	10.62

Table 14: Material balance on pump

	Inlet	Outlet
Pressure (kPa)	100	287.1
Temperature (°C)	24.97	25
Enthalpy (kw)	1064.81	1066.08

Table 15: Energy balance on pump

4.4.3 Material and Energy Balance Downstream to Diesel Power Plant

WRSB

	Inlet (kg/s)	Outlet (kg/s)
Hot Side		
	Flue gas	Flue gas
CO ₂	0.758	0.758
CO	0.002	0.002
H ₂ O	0.582	0.582
H ₂ SO ₃	0.004	0.004
H ₂ SO ₄	0.001	0.001
O ₂	0.173	0.173
N ₂	8.777	8.777
NO	0.001	0.001
Unburnt Fuel	5.703	5.703
Total	16.00	16.00
Cold Side		
Steam Produced	2.847	2.847

Table 16: Material balance on WRSB

	Inlet	Outlet
Hot Side		
Temperature (°C)	320.00	190.00
Flue Gas Enthalpy (kW)	7611.38	4096.50
Heat Lost (kW)	3400.62	
Cold Side		
Temperature (°C)	110.00	188.40
Steam Enthalpy (kW)	1013.37	4514.37
Heat Gained (kW)	3501.00	
Losses (kW)	13.89	

Table 17: Energy balance on WRSB

Economizer

	Inlet (kg/s)	Outlet (kg/s)
Hot Side		
	Flue gas	Flue gas
CO₂	0.758	0.758
CO	0.002	0.002
H₂O	0.582	0.582
H₂SO₃	0.004	0.004
H₂SO₄	0.001	0.001
O₂	0.173	0.173
N₂	8.777	8.777
NO	0.001	0.001
Unburnt Fuel	5.703	5.703
Total	16.00	16.00
Cold Side		
Boiler Feed Water	2.847	2.847

Table 18: Material balance on economizer

	Inlet	Outlet
Hot Side		
Temperature (°C)	190.00	160.00
Flue Gas Enthalpy (kW)	3985.47	3234.06
Heat Lost (kW)	774.52	
Cold Side		
Temperature (°C)	45.03	110.00
BFW Enthalpy (kW)	231.72	983.13
Heat Gained (kW)	774.52	

Table 19: Energy balance on economizer

Condenser

	Inlet (kg/s)	Outlet (kg/s)	
	Hot side		
	Flue gas	Flue gas	Condensate
CO₂	0.758	0.758	
CO	0.002	0.002	
H₂O	0.582	0.582	
H₂SO₃	0.004	-	0.004
H₂SO₄	0.001	-	0.001
O₂	0.173	0.173	
N₂	8.777	8.777	
NO	0.001	0.001	
Unburnt Fuel	5.703	5.703	
Total	16.00	16.00	
	Cold side		
Cooling Water	11.035	11.035	

Table 20: Material balance on condenser

	Inlet	Outlet
	Hot side	
Temperature (°C)	160.00	96.00
Flue Gas Enthalpy (kW)	3321.98	1473.91
Condensate Enthalpy (kW)	-	-19.63
Heat Lost (kW)	1848.06	
	Cold side	
Temperature (°C)	25.00	65.00
Cooling Water Enthalpy (kW)	0.00	1848.06
Heat Gained (kW)	1848.06	

Table 21: Energy balance on condenser

Pre-Heater

	Inlet (kg/s)	Outlet (kg/s)
	Hot Side	
Cooling Water	11.035	11.035
	Cold Side	
Make up water	5.517	5.517

Table 22: Material balance on pre-heater

	Inlet	Outlet
	Hot Side	
Temperature (°C)	65.00	55.00
Cooling water Enthalpy (kW)	1846.06	1386.05
Heat Lost (kW)	462.02	
	Cold Side	
Temperature (°C)	25.00	45.00
Make up Water Enthalpy (kW)	0.00	462.02
Heat Gained (kW)	462.02	

Table 23: Energy balance on pre-heater

De-Aerator

Inlet (kg/s)		Outlet (kg/s)	
Make up water	5.517	BFW	2.847
Condensate Steam	0.010	Plant water	2.680
Total	5.527	Purge	0.010
		Total	5.527

Table 24: Material balance on de-aerator

Inlet (kW)		Outlet (kW)	
Make up water	462.02	BFW	238.85
Condensate Steam	1.53	Re-Use	224.80
Total	463.55	Purge	1.53
		Total	463.55

Table 25: Energy balance on de-aerator

Pump

	Inlet	Outlet
Water (kg/s)	11.035	11.035

Table 26: Material balance on pump

	Inlet	Outlet
Pressure (kPa)	100	287.1
Temperature (°C)	24.97	25
Enthalpy (kw)	1064.81	1066.08

Table 27: Energy balance on pump

4.4.4 Material and Energy Balance Downstream to Natural Gas Power Plant

WRSB

	Inlet (kg/s)	Outlet (kg/s)
Hot Side		
	Flue gas	Flue gas
CO ₂	1.378	1.378
CO	0.001	0.001
H ₂ O	1.016	1.016
H ₂ SO ₃	8.55E-06	8.55E-06
H ₂ SO ₄	1.42E-06	1.42E-06
O ₂	0.400	0.400
N ₂	10.164	10.164
NO	0.013	0.013
Unburnt Fuel	3.027	3.027
Total	16.00	16.00
Cold Side		
Steam Produced	4.386	4.386

Table 28: Material balance on WRSB

	Inlet	Outlet
Hot Side		
Temperature (°C)	320.00	190.00
Flue Gas Enthalpy (kW)	12128.51	5332.69
Heat Lost (kW)	6795.82	
Cold Side		
Temperature (°C)	110.00	188.40
Steam Enthalpy (kW)	1560.788	8311.373
Heat Gained (kW)	6750.58	
Losses (kW)	13.89	

Table 29: Energy balance on WRSB

Economizer

	Inlet (kg/s)	Outlet (kg/s)
Hot Side		
	Flue gas	Flue gas
CO₂	1.378	1.378
CO	0.001	0.001
H₂O	1.016	1.016
H₂SO₃	8.55E-06	8.55E-06
H₂SO₄	1.42E-06	1.42E-06
O₂	0.400	0.400
N₂	10.164	10.164
NO	0.013	0.013
Unburnt Fuel	3.027	3.027
Total	16.00	16.00
Cold Side		
Boiler Feed Water	4.386	4.386

Table 30: Material balance on economizer

	Inlet	Outlet
Hot Side		
Temperature (°C)	190.00	160.00
Flue Gas Enthalpy (kW)	5332.689	4139.777
Heat Lost (kW)	1192.912	
Cold Side		
Temperature (°C)	45.03	110.00
BFW Enthalpy (kW)	367.877	1560.788
Heat Gained (kW)	1192.912	

Table 31: Energy balance on economizer

Condenser

	Inlet (kg/s)	Outlet (kg/s)	
	Hot side		
	Flue gas	Flue gas	Condensate
CO ₂	1.378	1.378	
CO	0.001	0.001	
H ₂ O	1.016	1.016	
H ₂ SO ₃	9.27E-07		9.27E-07
H ₂ SO ₄	1.42E-06		1.42E-06
O ₂	0.400	0.400	
N ₂	10.164	10.164	
NO	0.013	0.013	
Unburnt Fuel	3.027	3.027	
Total	16.00	16.00	
	Cold side		
Cooling Water	13.044	13.044	

Table 32: Material balance on condenser

	Inlet	Outlet
	Hot side	
Temperature (°C)	160.00	96.00
Flue Gas Enthalpy (kW)	4139.777	1955.225
Condensate Enthalpy (kW)	-	-2.46E-03
Heat Lost (kW)	2184.55	
	Cold side	
Temperature (°C)	25.00	65.00
Cooling Water Enthalpy (kW)	0.00	2184.552
Heat Gained (kW)	2184.55	

Table 33: Energy balance on condenser

Pre-Heater

	Inlet (kg/s)	Outlet (kg/s)
Hot Side		
Cooling Water	13.044	13.044
Cold Side		
Make up water	6.522	6.522

Table 34: Material balance on pre-heater

	Inlet	Outlet
Hot Side		
Temperature (°C)	65.00	55.00
Cooling water Enthalpy (kW)	2184.552	1638.414
Heat Lost (kW)	546.14	
Cold Side		
Temperature (°C)	25.00	45.00
Make up Water Enthalpy (kW)	0.00	546.138
Heat Gained (kW)	546.142	

Table 35: Energy balance on pre-heater

De-Aerator

Inlet (kg/s)		Outlet (kg/s)	
Make up water	6.522	BFW	4.386
Condensate Steam	0.010	Plant water	2.146
Total	6.532	Purge	0.010
		Total	6.532

Table 36: Material balance on de-aerator

Inlet (kW)		Outlet (kW)	
Make up water	546.14	BFW	367.88
Condensate Steam	1.53	Re-Use	180.04
Total	547.67	Purge	1.53
		Total	547.67

Table 37: Energy balance on de-aerator

Pump

	Inlet	Outlet
Water (kg/s)	13.044	13.044

Table 38: Material balance on pump

	Inlet	Outlet
Pressure (kPa)	100	287.1
Temperature (°C)	24.97	25
Enthalpy (kW)	1064.81	1066.08

Table 39: Energy balance on pump

5. Condenser Designing

5.1 Introduction

A condenser is an equipment that is used to bring phase change, from gas to liquid. It is used to extract latent heat from the stream and use this energy to heat the cold stream. This condenser can be used to separate a mixture of components with varying saturation temperature.

5.2 Types of Condensers

5.2.1 Shell and Tube Heat Exchangers

A shell and tube heat exchanger consists of a cylindrical shell with tube bundles passing through it. Fluid in the tubes is called tube side fluid, while the fluid in the shell is called shell side fluid. Preferably, hot fluid is kept in the tubes to reduce the heat lost to the environment. Shell fluid may flow co-currently, counter currently or cross to the tube side fluid.

5.2.2 Plate Type Heat Exchangers

A plate heat exchanger has series of plates or fins that give direction to the fluid to pass through. Second fluid passes in the channels made by the alternate plates.

5.3 Selection

Condenser type: Shell and tube

Tube-side fluid: Flue gas

5.3.1 Material Selection

Shell is containing water as the cooling agent, hence common Carbon Steel can be used to manufacture shell.

However, production of sulphur acids cause an oxidizing environment in the tubes. Most metals and their alloys can resist corrosion to some degree of oxidation and a relatively high degree of reduction. Hence in

such a high oxidizing environment, common metals and their alloys will fail.

Materials that can be used are: Titanium, INCONEL 625 and Stainless steel 904L

5.3.1.1 Comparison

	Titanium	INCONEL 625	Stainless Steel 904L
Major Components	Titanium	Nickle, Chromium and Iron	Carbon, Nickle, Chromium, Molybdenum, Manganese,
Service temperature (°C)	600 °C	982 °C	400 °C
Cost	High	Lower	Lowest
Ease of Availability	Lowest	Lower	High

Table 40: Comparison of Materials for condenser tubes

Material selected for tubes: **Stainless steel 904L**

5.4 Design Calculations

5.4.1 HFO Power Plant

Step 1. Extract fluid data

$$\dot{m}_{fg} = 16.0 \text{ kg/s}$$

$$\dot{m}_{H_2O} = 10.6 \text{ kg/s}$$

$$\dot{Q} = 1778.45 \text{ kJ/s}$$

$$T_1 = 160 \text{ °C}$$

$$T_2 = 96 \text{ °C}$$

$$t_1 = 25 \text{ °C}$$

$$t_2 = 65 \text{ °C}$$

Step 2. Collect the values of physical property

Flue gas:

$$\mu_t = 1.87 \times 10^{-5} \text{ kg/m s}$$

$$k_t = 2.6 \text{ W m/}^\circ\text{C}$$

$$c_p = 1.49 \text{ J/g}^\circ\text{C}$$

Water:

$$\mu_t = 5.065 \times 10^{-4} \text{ kg/m s}$$

$$k_t = 0.6484 \text{ W m/}^\circ\text{C}$$

$$c_p = 4.187 \text{ J/g}^\circ\text{C}$$

Step 3. Select exchanger type and fluid location

As mentioned previously,

Exchanger type: Shell and tube heat exchanger

Fluid location: Tube side fluid: Flue gas

Shell side fluid: Water

Step 4. Select an approximate value for U

$$U_{\text{approx}} = 45 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Step 5. Calculate LMTD and temperature correction factor

$$\text{LMTD} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left(\frac{T_1 - t_2}{T_2 - t_1}\right)}$$

$$\text{LMTD} = 82.42 \text{ }^\circ\text{C}$$

For correction factor,

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

$$R = 1.6$$

$$S = \frac{t_2 - t_1}{(T_1 - t_1)}$$

$$S = 0.3$$

$$F_t = 0.94$$

Step 6. Calculate preliminary area of the exchanger

$$Q = U \times A \times \text{LMTD} \times F_t$$

$$A = \frac{Q}{U \times \text{LMTD} \times F_t}$$

$$A = 510 \text{ m}^2$$

Step 7. Choose shell and tubes specifications

Tube: Material: SS-904L

$$d_{to} = 31.75 \text{ mm}$$

$$d_{tw} = 2 \text{ mm}$$

$$d_{ti} = 29.75 \text{ mm}$$

$$L = 7.5 \text{ m}$$

$$n_t = \frac{A}{\pi \times d_{to} \times L}$$

$$n_t = 154$$

Shell:

$$D_s = 0.4890 \text{ m}$$

$$N_p = 6$$

6 tube passes

Pitch: triangular

$$p_t = d_{to} \times 1.25$$

Segmental baffles 25%

$$\text{Baffle spacing} = 0.5 D_s = 0.2445 \text{ m}$$

Step 8. Calculate the individual heat transfer coefficients for each fluid

Tube fluid (Flue gas):

$$Re = \frac{G_t \times d}{\mu}$$

$$Re = 25,450$$

$$Pr = \frac{C_p \times \mu}{k}$$

$$Pr = 0.0106$$

$$\frac{\mu}{\mu_w} = 1$$

Using Sieder-Tate (1936) equation

$$Nu = C \times (Re)^{0.8} \times (Pr)^{0.33} \times \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$Nu = 17.96$$

$$Nu = \frac{h_t \times d_e}{k}$$

$$h_t = \frac{Nu \times d_e}{k}$$

$$h_t = 42.63 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

$$f = 0.0005$$

Shell fluid (Water):

$$A_s = \frac{p_t - d_{to} \times D_s \times l_B}{p_t}$$

$$A_s = 0.01155 \text{ m}^2$$

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

$$u_s = 0.9194 \text{ m/s}$$

$$d_e = \frac{1.10}{d_o} \times (p_t^2 - (0.917 \times d_{to}^2))$$

$$d_e = 0.023 \text{ m}$$

$$Re = \frac{G_s \times d_e}{\mu}$$

$$Re = 4.175 \times 10^4$$

$$Pr = \frac{Cp \times \mu}{k}$$

$$Pr = 3.271$$

$$j_h = 3 \times 10^{-3}$$

$$Nu = j_h \times Re \times (Pr)^{0.33} \times \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$Nu = 328$$

$$Nu = \frac{h_s \times d_e}{k}$$

$$h_s = \frac{Nu \times d_e}{k}$$

$$h_s = 4850 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

Step 9. Calculate U and find error (with respect to U_{approx})

$$U = \frac{1}{h_s} + \frac{1}{h_{sd}} + \frac{d_s \ln\left(\frac{d_s}{d_t}\right)}{2 \times k_w} + \frac{d_s}{d_t} \times \frac{1}{h_{td}} + \frac{d_s}{d_t} \times \frac{1}{h_t}$$

$$h_{sd} = 6000 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

$$h_{id} = 5000 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

$$k_w = 12.90 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

$$U = 38.78 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

$$\text{Error} = \frac{U_{\text{approx}} - U_{\text{calc}}}{U_{\text{approx}}} \times 100$$

$$\text{Error} = 13.3\%$$

Step 10. Calculate the pressure drop

Tube side:

$$\Delta P_t = N_p \times \left[(8 \times j_f \times \left(\frac{L'}{d_t}\right) \times \left(\frac{\mu}{\mu_w}\right)^{0.14}) + 2.5 \right] \times \frac{\rho \times u_t^2}{2}$$

$$\Delta P_t = 2725 \text{ Pa}$$

Shell side:

$$\Delta P_s = 8 \times j_f \times \left(\frac{D_s}{d_e}\right) \times \left(\frac{L}{l_B}\right) \times \left(\frac{\rho \times u_s^2}{2}\right) \times \left(\frac{\mu}{\mu_w}\right)^{-0.14}$$

$$\Delta P_s = 15650 \text{ Pa}$$

5.4.2 Diesel Power Plant

Step 1.

$$\dot{m}_{fg} = 16.0 \text{ kg/s}$$

$$\dot{m}_{H_2O} = 11.04 \text{ kg/s}$$

$$\dot{Q} = 1848.06 \text{ kJ/s}$$

$$T_1 = 160 \text{ }^\circ\text{C}$$

$$T_2 = 96 \text{ }^\circ\text{C}$$

$$t_1 = 25 \text{ }^\circ\text{C}$$

$$t_2 = 65 \text{ }^\circ\text{C}$$

Step 2.

Flue gas:

$$\mu_t = 1.85 \times 10^{-5} \text{ kg/m s}$$

$$k_t = 2.57 \text{ W m/}^\circ\text{C}$$

$$c_p = 1.53 \text{ J/g}^\circ\text{C}$$

Water:

$$\mu_s = 5.065 \times 10^{-4} \text{ kg/m s}$$

$$k_s = 0.6484 \text{ W m/}^\circ\text{C}$$

$$c_p = 4.187 \text{ J/g}^\circ\text{C}$$

Step 3.

Exchanger type: Shell and tube heat exchanger

Fluid location: Tube side fluid: Flue gas

Shell side fluid: Water

Step 4.

$$U_{\text{approx}} = 45 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Step 5.

$$\text{LMTD} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left(\frac{T_1 - t_2}{T_2 - t_1}\right)}$$

$$\text{LMTD} = 82.42 \text{ }^\circ\text{C}$$

For correction factor,

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

$$R = 1.6$$

$$S = \frac{t_2 - t_1}{(T_1 - t_1)}$$

$$S = 0.3$$

$$F_t = 0.94$$

Step 6.

$$Q = U \times A \times \text{LMTD} \times F_t$$

$$A = \frac{Q}{U \times \text{LMTD} \times F_t}$$

$$A = 530 \text{ m}^2$$

Step 7.

Tube: Material: SS-904L

$$d_{\text{to}} = 31.75 \text{ mm}$$

$$d_{\text{tw}} = 2 \text{ mm}$$

$$d_{\text{ti}} = 29.75 \text{ mm}$$

$$L = 7.5 \text{ m}$$

$$n_t = \frac{A}{\pi \times d_{to} \times L}$$

$$n_t = 162$$

Shell:

$$D_s = 0.4890 \text{ m}$$

$$N_p = 6$$

6 tube passes

Pitch: triangular

$$p_t = d_{to} \times 1.25$$

Segmental baffles

$$\text{Baffle spacing} = 0.5 D_s = 0.2445 \text{ m}$$

Step 8.

Tube fluid (Flue gas):

$$Re = \frac{G_t \times d}{\mu}$$

$$Re = 25,730$$

$$Pr = \frac{C_p \times \mu}{k}$$

$$Pr = 0.0110$$

$$\frac{\mu}{\mu_w} = 1$$

Using Sieder-Tate (1936) equation

$$Nu = C \times (Re)^{0.8} \times (Pr)^{0.33} \times \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$Nu = 16.01$$

$$Nu = \frac{h_t \times d_e}{k}$$

$$h_t = \frac{Nu \times d_e}{k}$$

$$h_t = 44.58 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Shell fluid (Water):

$$A_s = \frac{p_t - d_{to} \times D_s \times l_B}{p_t}$$

$$A_s = 0.01155 \text{ m}^2$$

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

$$u_s = 0.9558 \text{ m/s}$$

$$d_e = \frac{1.10}{d_o} \times (p_t^2 - (0.917 \times d_{to}^2))$$

$$d_e = 0.023 \text{ m}$$

$$Re = \frac{G_s \times d_e}{\mu}$$

$$Re = 4.341 \times 10^4$$

$$Pr = \frac{Cp \times \mu}{k}$$

$$Pr = 3.271$$

$$j_h = 3 \times 10^{-3}$$

$$Nu = j_h \times Re \times (Pr)^{0.33} \times \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$Nu = 402$$

$$Nu = \frac{h_s \times d_e}{k}$$

$$h_s = \frac{Nu \times d_e}{k}$$

$$h_s = 4934 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Step 9.

$$U = \frac{1}{h_s} + \frac{1}{h_{sd}} + \frac{D_s \ln\left(\frac{D_s}{d_t}\right)}{2 \times k_w} + \frac{D_s}{d_t} \times \frac{1}{h_{td}} + \frac{D_s}{d_t} \times \frac{1}{h_t}$$

$$h_{sd} = 6000 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$h_{id} = 5000 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$k_w = 12.90 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$U = 42.54 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$\text{Error} = \frac{U_{\text{approx}} - U_{\text{calc}}}{U_{\text{approx}}} \times 100$$

$$\text{Error} = 5.5\%$$

Step 10.

Tube side:

$$\Delta P_t = N_p \times \left[(8 \times j_f \times \left(\frac{L'}{d_t}\right) \times \left(\frac{\mu}{\mu_w}\right)^{0.14}) + 2.5 \right] \times \frac{\rho \times u_t^2}{2}$$

$$\Delta P_t = 3104 \text{ Pa}$$

Shell side:

$$\Delta P_s = 8 \times j_f \times \left(\frac{D_s}{d_e}\right) \times \left(\frac{L}{l_B}\right) \times \left(\frac{\rho \times u_s^2}{2}\right) \times \left(\frac{\mu}{\mu_w}\right)^{-0.14}$$

$$\Delta P_s = 15690 \text{ Pa}$$

5.4.3 Natural Gas Power Plant

Step 1.

$$\dot{m}_{fg} = 16.0 \text{ kg/s}$$

$$\dot{m}_{H_2O} = 13.04 \text{ kg/s}$$

$$\dot{Q} = 2185 \text{ kJ/s}$$

$$T_1 = 160 \text{ }^\circ\text{C}$$

$$T_2 = 96 \text{ }^\circ\text{C}$$

$$t_1 = 25 \text{ }^\circ\text{C}$$

$$t_2 = 65 \text{ }^\circ\text{C}$$

Step 2.

Flue gas: $\mu_t = 1.72 \times 10^{-5} \text{ kg/m s}$

$$k_t = 2.53 \text{ W m/}^\circ\text{C}$$

$$cp = 1.75 \text{ J/g}^\circ\text{C}$$

Water: $\mu_s = 5.065 \times 10^{-4} \text{ kg/m s}$

$$k_s = 0.6484 \text{ W m/}^\circ\text{C}$$

$$cp = 4.187 \text{ J/g}^\circ\text{C}$$

Step 3.

Exchanger type: Shell and tube heat exchanger

Fluid location: Tube side fluid: Flue gas

Shell side fluid: Waters

Step 4.

$$U_{approx} = 45 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Step 5.

$$LMTD = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left(\frac{T_1 - t_2}{T_2 - t_1}\right)}$$

$$LMTD = 82.42 \text{ }^\circ\text{C}$$

For correction factor,

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

$$R = 1.6$$

$$S = \frac{t_2 - t_1}{(T_1 - t_1)}$$

$$S = 0.3$$

$$F_t = 0.94$$

Step 6.

$$Q = U \times A \times LMTD \times F_t$$

$$A = \frac{Q}{U \times LMTD \times F_t}$$

$$A = 627 \text{ m}^2$$

Step 7.

Tube: Material: SS-904L

$$d_{to} = 31.75 \text{ mm}$$

$$d_{tw} = 2 \text{ mm}$$

$$d_{ti} = 29.75 \text{ mm}$$

$$L = 7.5 \text{ m}$$

$$n_t = \frac{A}{\pi \times d_{to} \times L}$$

$$n_t = 170$$

Shell:

$$D_s = 0.4890 \text{ m}$$

$$N_p = 6$$

6 tube passes

Pitch: triangular

$$p_t = d_{to} \times 1.25$$

Segmental baffles

$$\text{Baffle spacing} = 0.5 D_s = 0.2445 \text{ m}$$

Step 8.

Tube fluid (Flue gas):

$$Re = \frac{G_t \times d}{\mu}$$

$$Re = 27670$$

$$Pr = \frac{Cp \times \mu}{k}$$

$$Pr = 0.0119$$

$$\frac{\mu}{\mu_w} = 1$$

Using Sieder-Tate (1936) equation

$$Nu = C \times (Re)^{0.8} \times (Pr)^{0.33} \times \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$Nu = 17.41$$

$$Nu = \frac{h_t \times d_e}{k}$$

$$h_t = \frac{Nu \times d_e}{k}$$

$$h_t = 41.62 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

Shell fluid (Water):

$$A_s = \frac{p_t - d_{to} \times D_s \times l_B}{p_t}$$

$$A_s = 0.01155 \text{ m}^2$$

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

$$u_s = 1.130 \text{ m/s}$$

$$d_e = \frac{1.10}{d_o} \times (p_t^2 - (0.917 \times d_{to}^2))$$

$$d_e = 0.023 \text{ m}$$

$$Re = \frac{G_s \times d_e}{\mu}$$

$$Re = 5.133 \times 10^4$$

$$Pr = \frac{Cp \times \mu}{k}$$

$$Pr = 3.271$$

$$j_h = 3 \times 10^{-3}$$

$$Nu = j_h \times Re \times (Pr)^{0.33} \times \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$Nu = 227.6$$

$$Nu = \frac{h_s \times d_e}{k}$$

$$h_s = \frac{Nu \times d_e}{k}$$

$$h_s = 5002 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Step 9.

$$U = \frac{1}{h_s} + \frac{1}{h_{sd}} + \frac{D_s \ln\left(\frac{D_s}{d_t}\right)}{2 \times k_w} + \frac{D_s}{d_t} \times \frac{1}{h_{td}} + \frac{D_s}{d_t} \times \frac{1}{h_t}$$

$$h_{sd} = 6000 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$h_{id} = 5000 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$k_w = 12.90 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$U = 45.16 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$Error = \frac{U_{calc} - U_{approx}}{U_{approx}} \times 100$$

$$Error = 0.356\%$$

Step 10.

Tube side:

$$\Delta P_t = N_p \times \left[(8 \times j_f \times \left(\frac{L'}{d_t}\right) \times \left(\frac{\mu}{\mu_w}\right)^{0.14}) + 2.5 \right] \times \frac{\rho \times u_t^2}{2}$$

$$\Delta P_t = 3374 \text{ Pa}$$

Shell side:

$$\Delta P_s = 8 \times j_f \times \left(\frac{D_s}{d_e}\right) \times \left(\frac{L}{l_B}\right) \times \left(\frac{\rho \times u_s^2}{2}\right) \times \left(\frac{\mu}{\mu_w}\right)^{-0.14}$$

$$\Delta P_s = 16340 \text{ Pa}$$

5.5 Comparison of Condensers

Parameters	Power plant		
	HFO	DIESEL	NATURAL GAS
Area of condenser (m ²)	510	530	626
Number of tubes:	154	162	170
Tube side pressure drop (kPa)	2.725	3.104	3.374
Cooling water required (kg/s)	10.62	11.04	13.04
Shell side pressure drop (kPa)	15.65	15.72	16.34

Table 41: Comparison between condensers designed

6. Pre-Heater Design

6.1 Specifications

Type: Shell and tube

Tube-side fluid: Cold Water

Shell-side fluid: Make-up Water

Tubes Material: Stainless steel

Shell Material: Stainless steel

Stainless Steel Thermal Conductivity, $k_w = 45 \text{ W/m} \cdot ^\circ\text{C}$

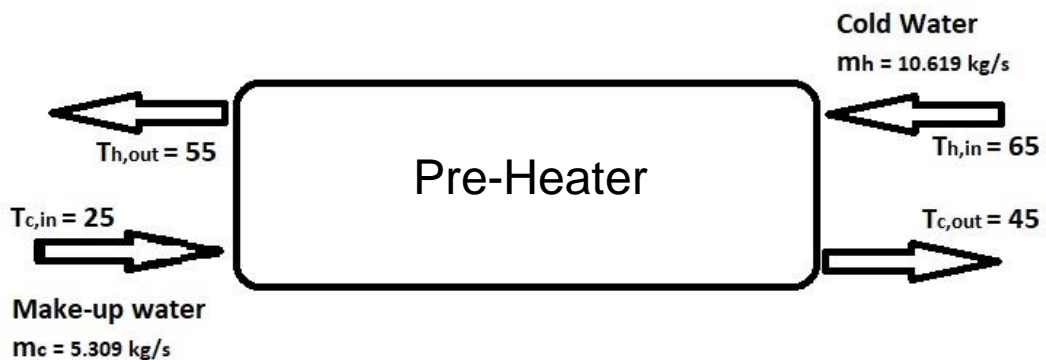


Figure 3. Pre-heater

Note: All temperatures are in $^\circ\text{C}$.

6.2 Design

6.2.1 HFO Power Plant

Design Calculations

Step 1.

$$\dot{m}_{cw} = 10.619 \text{ kg/s}$$

$$\dot{m}_{mw} = 5.309 \text{ kg/s}$$

$$\dot{Q} = 444.5 \text{ kJ/s}$$

$$T_1 = 65 \text{ }^\circ\text{C}$$

$$T_2 = 55 \text{ }^\circ\text{C}$$

$$t_1 = 25 \text{ }^\circ\text{C}$$

$$t_2 = 45 \text{ }^\circ\text{C}$$

Step 2.

Water (Shell and tube side):

$$\mu_w = 8.90 \times 10^{-4} \text{ kg/m s}$$

$$k_w = 45 \text{ W m/}^\circ\text{C}$$

$$c_p = 4.187 \text{ kJ/kg}^\circ\text{C}$$

Step 3.

$$U_{\text{approx}} = 1300 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Step 4.

$$\text{LMTD} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left(\frac{T_1 - t_2}{T_2 - t_1}\right)}$$

$$\text{LMTD} = 24.66 \text{ }^\circ\text{C}$$

For correction factor,

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

$$R = 2$$

$$S = \frac{t_2 - t_1}{(T_1 - t_1)}$$

$$S = 0.25$$

$$F_t = 0.98$$

Step 5.

$$Q = U \times A \times \text{LMTD} \times F_t$$

$$A = \frac{Q}{U \times \text{LMTD} \times F_t}$$

$$A = 14.13 \text{ m}^2$$

Step 6.

Tubes:

Pattern of tube pitch: Triangular

$$p_t = d_{to} \times 1.25$$

$$d_{to} = 0.0125 \text{ m}$$

$$d_{ti} = 0.00925 \text{ m}$$

$$\text{BWG} = 16$$

$$L = 2 \text{ m}$$

$$p_t = 0.015625 \text{ m}$$

$$n_t = \frac{A}{\pi \times d_{to} \times L}$$

$$n_t = 180$$

Shell:

$$D_b = d_{to} \left(\frac{n_t}{K_1} \right)^{1/n_1}$$

For four tube-passes:

$$K_1 = 0.175$$

$$n_1 = 2.285$$

Hence,

$$D_b = 0.2601 \text{ m}$$

$$D_s = D_b + \text{BDC}$$

$$\text{BDC} = 0.012$$

$$D_s = 0.4890 \text{ m}$$

Baffle spacing = 0.5

$$l_B = 0.10884$$

Step 7.

Tube fluid (Flue gas):

$$\text{Re} = \frac{G_t \times d}{\mu} \quad \text{where, } G_t = 3511.54 \text{ kg/m}^2 \text{ s}$$

$$\text{Re} = 36496$$

$$\text{Pr} = \frac{C_p \times \mu}{k}$$

$$\text{Pr} = 0.000083$$

$$\frac{\mu}{\mu_w} = 1$$

Using Sieder-Tate (1936) equation

$$\text{Nu} = C \times (\text{Re})^{0.8} \times (\text{Pr})^{0.33} \times \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$\text{Nu} = 2.34717$$

$$h_t = \frac{\text{Nu} \times d_e}{k}$$

$$h_t = 22538.85 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Shell fluid (Water):

$$A_s = \frac{(p_t - d_{to}) \times D_s \times B_s}{p_t}$$

$$A_s = 0.0059 \text{ m}^2$$

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

$$G_s = 899.83 \text{ kg/m}^2 \text{ s}$$

$$u_s = 0.9 \text{ m/s}$$

$$d_e = \frac{1.10}{d_o} \times (p_t^2 - (0.917 \times d_{to}^2))$$

$$d_e = 0.008879 \text{ m}$$

$$Re = \frac{G_s \times d_e}{\mu}$$

$$Re = 8976$$

$$Pr = \frac{C_p \times \mu}{k}$$

$$Pr = 0.0000828$$

$$j_f = 5$$

(for 25% baffle cut)

$$Nu = j_f \times Re \times (Pr)^{0.33} \times \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$Nu = 2.34717$$

$$Nu = \frac{h_s \times d_e}{k}$$

$$h_s = \frac{Nu \times k}{d_e}$$

$$h_s = 11899.803 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Step 8.

$$\frac{1}{U} = \frac{1}{h_t} + \frac{1}{h_{id}} + \frac{d_t \ln\left(\frac{d_s}{d_t}\right)}{2 \times k_w} + \frac{d_t}{d_s} \times \frac{1}{h_{sd}} + \frac{d_t}{d_s} \times \frac{1}{h_s}$$

$$h_{sd} = 3000 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$h_{id} = 3000 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$k_w = 45 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$U = 1393.73 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$\text{Error} = \frac{U_{\text{approx}} - U_{\text{calc}}}{U_{\text{approx}}} \times 100$$

$$\text{Error} = 7.2 \%$$

Step 9.

Tube side:

$$\Delta P_t = N_p \times \left[(8 \times j_f \times \left(\frac{L'}{d_t}\right) \times \left(\frac{\mu}{\mu_w}\right)^{0.14}) + 2.5 \right] \times \frac{\rho \times u_t^2}{2}$$

$$\Delta P_t = 5.19 \text{ kPa}$$

Shell side:

$$\Delta P_s = 8 \times j_f \times \left(\frac{D_s}{d_e}\right) \times \left(\frac{L}{l_B}\right) \times \left(\frac{\rho \times u_s^2}{2}\right) \times \left(\frac{\mu}{\mu_w}\right)^{-0.14}$$

$$\Delta P_s = 10.21 \text{ kPa}$$

6.2.2 Diesel Power Plant

$$\dot{Q} = 462.02 \text{ kJ/s}$$

$$A = 33.15 \text{ m}^2$$

$$n_t = 422 \text{ tubes}$$

$$D_s = 0.3907 \text{ m}$$

6.2.3 Natural Gas Power Plant

$$\dot{Q} = 546.138 \text{ kJ/s}$$

$$A = 39.185 \text{ m}^2$$

$$n_t = 499 \text{ tubes}$$

$$D_s = 0.4194 \text{ m}$$

6.3 Comparison of Pre-Heaters

Parameters	Power Plant		
	HFO	DIESEL	NATURAL GAS
Area of heater (m ²)	28.00	33.15	39.19
Number of tubes:	360	422	499
Tube side pressure drop (kPa)	5.19	6.24	7.54
Make up water heated (kg/s)	5.31	5.52	6.52
Shell side pressure drop (kPa)	10.21	13.59	16.38

Table 42: Comparison between pre-heaters designed

7. Pump Design

7.1 HFO Power Plant

Step 1: Data Collection

Commercial steam pipe

Internal diameter (**assumed**) = 125 mm

L (**assumed**) = 100m

2 × 45° standard elbows (**assumed**)

1 × gate valve fully opened (**assumed**)

$P_1 = 100 \text{ Pa}$

$P_2 = 287.1 \text{ Pa}$

$z_1 = 0 \text{ m}$

$z_2 = 10 \text{ m}$

$\eta = 0.65$

$P_v = 3.173 \text{ kPa}$

Step 2: Finding the friction factor

$$\text{Area of pipe} = \frac{\pi}{4} \times (d^2)$$

$$\text{Area of pipe} = 0.01227 \text{ m}^2$$

$$u = \frac{G}{\rho}$$

$$u = 0.828 \text{ m/s}$$

$$Re = \frac{\rho u d}{\mu}$$

$$Re = 2.04 \times 10^5$$

$$\text{Absolute roughness} = 0.046 \text{ mm}$$

$$f = 0.0024$$

Step 3: Calculating the head loss due to friction

Number of equivalent pipe diameters:

$$\text{Entry} = 25$$

$$45^\circ \text{ standard elbow} = 15$$

$$\text{Gate valve (fully open)} = 7.5$$

$$\text{Exit} = 50$$

$$L_{Misc} = \text{Entry} + \text{Elbows} + \text{Valve} + \text{Exit}$$

$$L_{Misc} = 112.5$$

$$L_T = L + (L_{Misc} \times d_i)$$

$$L_T = 125.31m$$

$$\Delta P_f = 8 \times f \times \frac{L_T}{d} \times \rho \times \frac{u^2}{2}$$

$$\Delta P_f = 6.60 \text{ kPa}$$

Step 4: Calculating changes in height and pressure

$$\Delta z = z_1 - z_2$$

$$\Delta z = 10m$$

$$\Delta P = P_1 - P_2$$

$$\Delta P = -187.1 \text{ kPa}$$

Step 5: Calculating work and power

$$W = g\Delta z + \frac{\Delta P}{\rho} - \frac{\Delta P_f}{\rho}$$

$$W = -291.8 \text{ J/kg}$$

$$\text{Power} = \frac{W \times \dot{m}}{\eta}$$

$$\text{Power} = 4.76 \text{ kW}$$

Step 6: Calculating available NPSH

$$NPSH_{avail} = H + \frac{P}{\rho} - \frac{P_f}{\rho} - \frac{P_v}{\rho}$$

$$NPSH_{avail} = 21.5 \text{ m}$$

7.2 Diesel Power Plant

$$u = 0.864 \text{ m/s}$$

$$W = 294.2 \text{ J/kg}$$

$$\text{Power} = 5.17 \text{ kW}$$

$$NPSH_{avail} = 21.5 \text{ m}$$

7.3 Natural Gas Power Plant

$$u = 1.02 \text{ m/s}$$

$$W = 299.4 \text{ J/kg}$$

$$\text{Power} = 6.00 \text{ kW}$$

$$\text{NPSH}_{\text{avail}} = 21.5 \text{ m}$$

7.4 Comparison of Pumps

Following table shows the comparison between pumps required for three power plants.

Parameters	Power Plant		
	HFO	Diesel	Natural Gas
u (m/s)	0.828	0.864	1.02
W (J/kg)	291.8	294.2	299.4
Power (kW)	4.76	5.17	6.00
NPSH _{avail} (m)	21.5	21.5	21.5

Table 43: Comparison between pumps designed

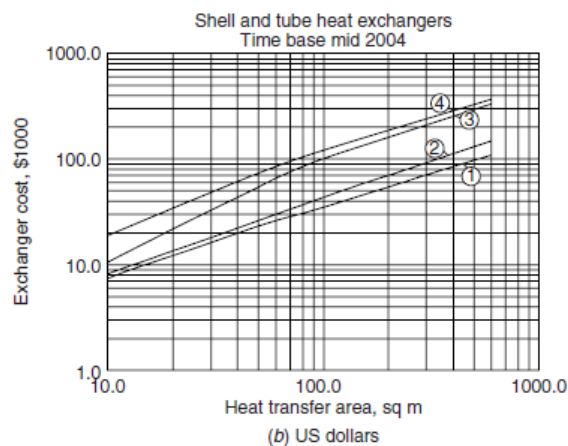
8. Economics

8.1 Flue Gas Source: HFO

8.1.1 Condenser Equipment Cost

Type of condenser = Shell and Tube heat exchanger

Exchanger area = 510 m²



Materials		Pressure factors		Type factors	
Shell	Tubes				
① Carbon steel	Carbon steel	1–10 bar	× 1.0	Floating head	× 1.0
② C.S.	Brass	10–20	× 1.1	Fixed tube sheet	× 0.8
③ C.S.	Stainless steel	20–30	× 1.25	U tube	× 0.85
④ S.S.	S.S.	30–50	× 1.3	Kettle	× 1.3
		50–70	× 1.5		

Figure 4. Condenser costing graph

Total condenser cost = \$120,000

8.1.2 Condenser Running Cost

Cooling water required: 10.61 kg/s

Cooling water price: 1C/ton

Annual cooling water expenditure: \$3,263.00 /year

8.1.3 Sulphuric Acid Payback

Current sulphuric acid cost: \$65/ton

Assuming 0.053 kg/s of sulphuric acid usage (equals to amount produced by condenser)

Annual saving by sulphuric acid production: \$108,100.00/year

8.1.4 Payback Period

$$\text{Payback period} = \frac{\text{Equipment cost}}{\text{Annual earning}}$$

$$\text{Payback period} = 1.11 \text{ years}$$

8.2 Flue Gas Source: Diesel

8.2.1 Condenser Equipment Cost

Type of condenser = Shell and Tube heat exchanger

Exchanger area = 530 m²

$$\text{Total condenser cost} = \$125,000$$

8.2.2 Condenser Running Cost

Cooling water required: 11.04 kg/s

Cooling water price: 1C/ton

Annual cooling water expenditure: \$3,396.00 /year

8.2.3 Sulphuric Acid Payback

Current sulphuric acid cost: \$65/ton

Assuming 0.006 kg/s of sulphuric acid usage

Annual saving by sulphuric acid production: \$12,000.00 /year

8.2.4 Payback Period

$$\text{Payback period} = 10.4 \text{ years}$$

8.3 Flue Gas Source: Natural Gas

8.3.1 Condenser Equipment Cost

Type of condenser = Shell and Tube heat exchanger

Exchanger area = 627 m²

$$\text{Total condenser cost} = \$145,000$$

8.3.2 Condenser Running Cost

Cooling water required: 13.04 kg/s

Cooling water price: 1C/ton

Annual cooling water expenditure: \$4,011.00 /year

8.3.3 Sulphuric Acid Payback

Current sulphuric acid cost: \$65/ton

Assuming 0.000097 kg/s of sulphuric acid usage

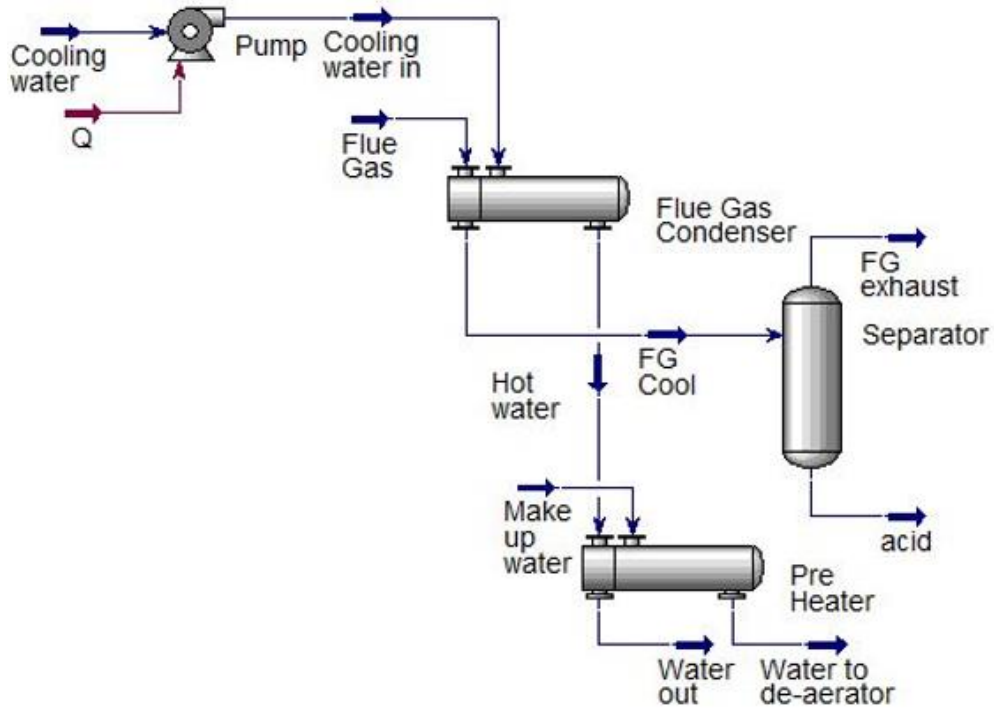
Annual saving by sulphuric acid production: \$19.39/year

8.3.4 Payback Period

Payback period = 14.0 years

9. Simulation

Package: PR-Twu



9.1 Equipment worksheet

9.1.1 Pump

Pump: Pump					
	Design	Rating	Worksheet	Performance	Dynamics
Worksheet	Name	Cooling water	Cooling water in	Q	
Conditions	Vapour	0.0000	0.0000	<empty>	
Properties	Temperature [C]	24.97	25.00	<empty>	
Composition	Pressure [kPa]	100.0	287.1	<empty>	
PF Specs	Molar Flow [kgmole/h]	2030	2030	<empty>	
	Mass Flow [kg/h]	3.658e+004	3.658e+004	<empty>	
	Std Ideal Liq Vol Flow [m3/h]	36.65	36.65	<empty>	
	Molar Enthalpy [kJ/kgmole]	-2.859e+005	-2.859e+005	<empty>	
	Molar Entropy [kJ/kgmole-C]	54.61	54.61	<empty>	
	Heat Flow [kJ/h]	-5.805e+008	-5.805e+008	1.045e+004	

9.1.2 Flue Gas Condenser

Heat Exchanger: FG Condenser

Design	Rating	Worksheet	Performance	Dynamics	Rigorous Shell&Tube	
Worksheet		Name	Flue Gas	FG Cool	Cooling water in	Hot water
Conditions		Vapour	1.0000	0.9985	0.0000	0.0000
Properties		Temperature [C]	160.0	96.33	25.00	65.00
Composition		Pressure [kPa]	110.0	94.35	287.1	284.4
PF Specs		Molar Flow [kgmole/h]	1244	1244	2030	2030
		Mass Flow [kg/h]	5.760e+004	5.760e+004	3.658e+004	3.658e+004
		Std Ideal Liq Vol Flow [m3/h]	105.2	105.2	36.65	36.65
		Molar Enthalpy [kJ/kgmole]	-7.286e+004	-7.784e+004	-2.859e+005	-2.828e+005
		Molar Entropy [kJ/kgmole-C]	201.6	190.5	54.61	64.22
		Heat Flow [kJ/h]	-9.062e+007	-9.681e+007	-5.805e+008	-5.743e+008

9.1.3 Pre Heater

Heat Exchanger: Pre Heater

Design	Rating	Worksheet	Performance	Dynamics	Rigorous Shell&Tube	
Worksheet		Name	Hot water	Water out	Make up water	Water to de-aerat
Conditions		Vapour	0.0000	0.0000	0.0000	0.0000
Properties		Temperature [C]	65.00	55.00	25.00	45.00
Composition		Pressure [kPa]	284.4	274.4	100.0	95.00
PF Specs		Molar Flow [kgmole/h]	2030	2030	998.1	998.1
		Mass Flow [kg/h]	3.658e+004	3.658e+004	1.798e+004	1.798e+004
		Std Ideal Liq Vol Flow [m3/h]	36.65	36.65	18.02	18.02
		Molar Enthalpy [kJ/kgmole]	-2.828e+005	-2.836e+005	-2.859e+005	-2.844e+005
		Molar Entropy [kJ/kgmole-C]	64.22	61.95	54.61	59.60
		Heat Flow [kJ/h]	-5.743e+008	-5.758e+008	-2.853e+008	-2.838e+008

9.2 Material Stream for Acid

9.2.1 Flue Gas Source: HFO

Material Stream: Acid

Worksheet	Attachments	Dynamics		
Worksheet		Stream Name	Acid	Vapour Phase
Conditions		Vapour / Phase Fraction	0.0000	0.0000
Properties		Temperature [C]	96.33	96.33
Composition		Pressure [kPa]	94.35	94.35
Oil & Gas Feed		Molar Flow [kgmole/h]	1.879	0.0000
Petroleum Assay		Mass Flow [kg/s]	4.985e-002	0.0000
K Value		Std Ideal Liq Vol Flow [m3/h]	9.796e-002	0.0000
User Variables		Molar Enthalpy [kJ/kgmole]	-8.055e+005	-7.674e+004
Notes		Molar Entropy [kJ/kgmole-C]	21.14	190.7
Cost Parameters		Heat Flow [kJ/h]	-1.513e+006	0.0000
Normalized Yields		Liq Vol Flow @Std Cond [m3/h]	9.495e-002	0.0000
		Fluid Package	Basis-1	

9.2.2 Flue Gas Source: Diesel

The screenshot shows the 'Material Stream: Acid' window in Aspen Plus. The 'Worksheet' tab is active, displaying a table of properties for the 'Acid' stream. The stream is in the 'Vapour Phase'.

Worksheet	Stream Name	Acid	Vapour Phase
Conditions	Vapour / Phase Fraction	0.0000	0.0000
Properties	Temperature [C]	96.33	96.33
Composition	Pressure [kPa]	94.35	94.35
Oil & Gas Feed	Molar Flow [kgmole/h]	1.879	0.0000
Petroleum Assay	Mass Flow [kg/h]	179.5	0.0000
K Value	Std Ideal Liq Vol Flow [m3/h]	9.796e-002	0.0000
User Variables	Molar Enthalpy [kJ/kgmole]	-8.055e+005	-7.674e+004
Notes	Molar Entropy [kJ/kgmole-C]	21.14	190.7
Cost Parameters	Heat Flow [kJ/h]	-1.513e+006	0.0000
Normalized Yields	Liq Vol Flow @Std Cond [m3/h]	9.495e-002	0.0000
	Fluid Package	Basis-1	
	Utility Type		

9.2.3 Flue Gas Source: Natural Gas

The screenshot shows the 'Material Stream: Acid' window in Aspen Plus. The 'Worksheet' tab is active, displaying a table of properties for the 'Acid' stream. The stream is in the 'Vapour Phase'.

Worksheet	Stream Name	Acid	Vapour Phase
Conditions	Vapour / Phase Fraction	0.0000	0.0000
Properties	Temperature [C]	97.54	97.54
Composition	Pressure [kPa]	94.35	94.35
Oil & Gas Feed	Molar Flow [kgmole/h]	0.0000	0.0000
Petroleum Assay	Mass Flow [kg/s]	0.0000	0.0000
K Value	Std Ideal Liq Vol Flow [m3/h]	0.0000	0.0000
User Variables	Molar Enthalpy [kJ/kgmole]	-2.817e+005	-4.156e+004
Notes	Molar Entropy [kJ/kgmole-C]	71.34	178.7
Cost Parameters	Heat Flow [kJ/h]	-0.0000	0.0000
Normalized Yields	Liq Vol Flow @Std Cond [m3/h]	0.0000	0.0000
	Fluid Package	Basis-1	
	Utility Type		

10. HAZOP Study

Parameter	Deviation	Causes	Consequences	Action
Cooling Water Flow	More	High pressure breaks control valve	Excessive heating of make-up water	Install more valves on line
	Less	Leakage Less supply	Condenser does not condensate SO _x	Maintenance of line to prevent corrosion

Table 44: Study on cooling water flows

Parameter	Deviation	Causes	Consequences	Action
Make-up Water Flow	More	High pressure breaks control valve	Condensation of SO _x in economizer Corrosion	Install flow meters and alarms
	Less	Leakage	Desired output temperature not obtained in Economizer and WRSB, hence no condensation of SO _x in condenser	Line maintenance against corrosion Painting the surface

Table 45: Study on make-up water flows

Parameter	Deviation	Causes	Consequences	Action
Cooling Water Temperature	More	Summers	<p>SO_x not condensed completely</p> <p>More SO_x discharged to stack. Less flow to neutralizer</p> <p>Damage to neutralizer</p> <p>Excess heating of makeup water</p>	<p>Fuel quality control</p> <p>Air (Oxygen) supply to boiler reduced</p>
	Less	Winters	<p>Cracking of pipes</p> <p>Clogging of pipes</p>	<p>Proper lagging of pipeline</p> <p>Warming of water reservoir</p>

Table 46: Study on cooling water temperature

Parameters	Deviation	Causes	Consequences	Action
Flue Gas Temperature	More	Excess Oxygen supply to boiler High calorific value of fuel	Little or no condensation of SO _x in condenser No feed to neutralizer Basic agent loss in neutralizer Excess heating of cooling water	Fuel quality control Reduce air (Oxygen) supply
	Less	Incomplete combustion inside boiler heat loss to surrounding Excess air leading to more nitrogen in boiler and flue gas	Condensation in economizer leading to corrosion Lower temperature of cooling water at the condenser outlet	Control air supply to boiler Ensure lagging of pipes from turbine to boiler Good residence time of fuel for efficient combustion Use fuel with appropriate calorific value

Table 47: Study on flue gas temperature

11. Conclusion

Parameters	Flue gas source		
	HFO	Diesel	Natural Gas
Condenser area (m ²)	510	530	626
Equipment cost (\$)	120,000.00	125,000.00	145,000.00
Annual running cost (\$/year)	3,263.00	3,396.00	4,011.00
Acid recovered (kg/s)	0.526	0.006	9.97x10 ⁻⁶
Cost of equivalent kg of acid (\$/year)	1,052,000.00	12,000.00	19.39

Table 48. Feasibility comparison of condenser for different fuels

It can be seen that the smallest condenser will be required downstream to the power plant burning HFO, and hence it has the lowest equipment cost. The largest will be present at the Natural Gas plant with highest equipment cost. Simultaneously, since HFO has highest sulphur content, highest amount of acid is collected from this condenser. Since these acids will be used in waste water treatment where acid is brought from external parties, it can be seen that annually \$1,052,000.00 will be saved by the industry.

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