DESIGN A GAS TURBINE GENERATOR AIR PREHEATING SYSTEM AND HEAT RECOVERY STEAM GENERATOR WITH FLUE GAS STACK RECOVERY

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CERTIFICATE

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DEDICATION

This work is dedicated to our parents for always believing in us, our teachers, for broadening our *perspective of the world and our tireless hard work.*

ACKNOWLEDGEMENT

We would like to begin by expressing our deepest gratitude to the Almighty for His boundless kindness. We recognize that without His guidance and blessings, our project would not have succeeded. His mercy has been our guiding light throughout this endeavor.

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ABSTRACT

The project has two major units in it, namely ‘Gas Turbine’ & ‘HRSG’. The GTG is a critical component in modern power generation, converting natural gas or other fuels into mechanical energy, which in turn drives an electric generator. Our design emphasizes efficiency and reliability, integrating advanced materials and technologies to maximize energy output while minimizing emissions. This ensures that the GTG operates within stringent environmental regulations and meets the growing demand for cleaner energy solutions.

The HRSG component complements the GTG by capturing and utilizing the waste heat produced during the gas turbine's operation. This heat is used to generate steam, which can be employed for additional power generation or industrial processes, enhancing overall system efficiency. Our project includes a comprehensive analysis of thermodynamic cycles, material selection, and heat transfer mechanisms to optimize the HRSG's performance. By combining these two systems, our design aims to provide a highly efficient and sustainable power generation solution that leverages the synergistic benefits of GTG and HRSG technologies.

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CHAPTER 1

INTRODUCTION

1.1 Background

The increasing demand for electricity and the need to reduce greenhouse gas emissions have led to the development of more efficient and environmentally friendly power generation technologies. Gas turbines are widely used for power generation due to their high efficiency and flexibility. However, they also produce significant amounts of heat that can be recovered and utilized to generate steam, which can be used for various industrial processes or even power generation itself. This heat recovery process is known as heat recovery steam generation (HRSG).

HRSGs are commonly used in combined cycle power plants to improve efficiency and reduce emissions. However, the design and optimization of HRSGs are complex tasks that require careful consideration of various factors, including the gas turbine's performance, the HRSG's design and configuration, and the integration of the two systems. The efficient design and operation of HRSGs are crucial for achieving optimal performance and minimizing environmental impacts.

1.2 Problem Statement

Despite the importance of HRSGs, there ae several challenges associated with their design and operation. Some of the key issues include:

- **Optimization of HRSG design:** The design of HRSGs is a complex task that requires careful consideration of various factors, including the gas turbine's performance, the HRSG's design and configuration, and the integration of the HRSG, and the gas turbine's performance, and the operating conditions.
- **Heat recovery efficiency:** The efficiency of heat recovery is critical for achieving optimal performance and minimizing environmental impacts. However, the efficiency

of heat recovery can be affected by various factors, including the design and configuration of the HRSG, the gas turbine's performance, and the operating conditions.

- **Cost-effectiveness:** The cost-effectiveness of HRSGs is another critical issue. The design and operation of HRSGs must be optimized to minimize costs while achieving optimal performance and minimizing environmental impacts.

1.3 Aim of the Project:

The aim of this project is to design and optimize a gas turbine generator and heat recovery steam generator through flue gas stack heat recovery. The project aims to:

- Design an optimal HRSG: Design an optimal HRSG that maximize heat recovery efficiency and minimize costs.
- Optimize HRSG Operation: Optimize the operation of the HRSG to achieve optimal performance and minimize environmental impacts.
- Integrate the Gas Turbine and the HRSG: Integrate the gas turbine and HRSG to ensure efficient heat recovery and optimal performance.
- Evaluate the Performance of the System: Evaluate the performance of the system in terms of heat recovery efficiency, power generation, and environmental impacts.

1.4 Applications of CCGT:

Following are some applications of CCGT:

- **Power Generation**: CCGT is widely used for power generation due to its high efficiency and flexibility. It can be used to generate electricity in various settings, including industrial, commercial, and residential areas.
- **Industrial Processes:** CCGT can be used to provide heat and power for various industrial processes, such as chemical processing, oil refining and paper manufacturing.

- **Commercial and Residential Buildings:** CCGT can be used to provide heating, cooling and power for commercial and residential buildings, reducing the need for separate heating and cooling systems.
- **Data Centers and Telecommunications:** CCGT can be used to provide reliable and efficient power for data centers and telecommunications facilities, ensuring continuous operation and minimizing downtime.
- **Agricultural and Food Processing:** CCGT an be used to provide power and heat for agricultural and food processing facilities, improving efficiency and reducing energy costs.

CHAPTER 2

LITERATURE REVIEW

2.1 Combined Cycle Gas Turbine power plant:

Combined Cycle Gas Turbine (CCTG) power plants are widely recognized for their efficiency and reduced environmental impact in electricity generation. These plants integrate a gas turbine and steam turbine in single cycle, using the waste heat from the gas turbine to produce steam that drives the steam turbine. This configuration significantly enhances the overall thermal efficiency and reduces fuel consumption compared to traditional power generation methods.

2.1.1 Efficiency and performance

The primary advantage of CCTG power plants lies in their high thermal efficiency, typically ranging from 50% to 60%, and in some advanced setups, reaching up to 62% to 65%. The combination of gas and steam turbines allows for the recovery of waste heat, which would otherwise be lost in simple cycle gas turbine. This recovery process not only boosts efficiency but also contributes to lower greenhouse gas emissions per unit of electricity generated.

2.1.2 Technological Advancements

Technological innovations have played a crucial role in the development of CCGT plants. Advances in gas turbine material, aerodynamics, and cooling technologies have allowed for higher operating temperatures and pressures, directly contributing to improved efficiency and reliability. Additionally, the integration of advanced control systems and predictive maintenance technologies has enhanced operational flexibility and reduced downtime.

2.1.3 Environmental Impact

CCTG power plants are considered more environmentally friendly than traditional coal-fired power plant. The use of natural gas, which has lower carbon emissions compared to coal, results in significantly lower CO2 emissions. Furthermore, the higher efficiency of CCGT plants reduces the amount of fuel needed to generate electricity, thereby decreasing the overall environmental footprint. The reduction in other pollutants, such as NOx and SOx, also makes CCGT plants a cleaner option for power generation.

2.1.4 Economic Viability

The economic benefits of CCGT power plants stem from their higher efficiency and lower operational costs. The ability to produce more electricity from the same amount of fuel translates into cost savings for power producers. Moreover, the shorter construction times and lower capital costs compared to nuclear and coal-fired plants make CCGT an attractive option for new power generation capacity. Additionally, the flexibility of CCGT plants to ramp up and down quickly in response to demand changes makes them suitable for integrating with renewable energy source.

2.1.5 Challenges and Future Directions

Despite their advantages, CCGT power plants face several challenges. The reliance on natural gas as a primary source of raises concerns about fuel price volatility and supply security. Additionally, the integration of renewable energy sources poses a challenge in terms of grid stability and the need for flexible and responsive power generation systems.

Future developments in CCGT technology are likely to focus on further improving efficiency, reducing emissions, and enhancing fuel flexibility. Research into alternative fuels, such as hydrogen, and the integration of carbon capture and storage (CCS) technologies are potential avenues for making CCGT plants even more sustainable.

2.2 Advantages of Combined Cycle Gas-Steam Power Plant:

Following are some advantages:

- High overall plant efficiency
- Low environmental impact
- Low investment cost

- A small amount of water is required.
- Large output

CHAPTER 3

PROCESS DESCRIPTION

3.1 Gas Turbine

An example of internal combustion engine is a gas turbine engine. In essence, the engine may be seen as an energy-transformation device that converts fuel-stored energy into useful mechanical energy, such as rotational strength. The term "gas" refers to the ambient air that enters the engine and serves as the working medium throughout the energy conversion process.

Initially, the engine draws in this air, packs it, mixes it with gasoline, and ignites it. The ensuing hot gas expands quickly along a series of sharp edges generated by air foils, transferring ignition energy to rotate an output shaft. It is possible to harness the residual thermal energy in the heated exhaust gas for a variety of mechanical operations.

3.1.1 Fundamental components:

- **Compressor** The compressor uses a series of stationary and pivoting compressor edges to first take in air, then compress and pressurize the air atoms.
- **Combustor** Fuel is introduced to the compressed air particle in the combustion and ignited. The heated particles expand and enter the turbine quickly.
- **Turbine** The turbine transforms the high-speed gas's energy into useful rotating power, on the other hand, is the result of extending the heated compressed gas along a series of turbine rotor edges.
- **Output Shaft and Gearbox** The turbine portion transfers rotational power to the driving hardware, through a speed-reducing gearing on the output shaft.
- **Exhaust** The exhaust region of the engine synchronizes the release gas from the turbine section as well as into the atmosphere.

3.1.2 Turbine Types:

There are several different types of turbines:

- It’s quite likely that you are familiar with the steam turbines. Most power plants use an atomic reactor, coal, oil, or combustible gas to generate steam. The steam powers a yield shaft that turns the plant generator after passing through a massive, designed multi-stage turbine.
- Water turbines are also used in hydroelectric dams to provide control. Because water is so denser and moves very slowly than steam, the turbine used in hydroelectric plants seem completely different from steam turbines, yet principles are the same.
- Wind is the source of power for wind turbines, often known as windmills. A wind turbine does not look at all like a steam turbine since wind is moderate moving and light, however, once more, the rule is the same.

The idea of gas turbine emerged from it. In a gas turbine pressurized gas turns the turbine. In every cutting-edge gas turbine motor, the motor delivers its own pressurized gas, and it does this by consuming something like propane, flammable gas, lamp oil or other fuel. The warmth that originates from consuming the fuel extends air, and the fast surge of this hot air turns the turbine.

3.1.3 Working Principle:

The motor of the gas turbine gets their power from consuming fuel in an ignition chamber and utilizing the quick streaming burning gases to drive a turbine. A straightforward gas turbine is included in the fundamental areas a compressor, a combustor and a power turbine. The gas turbine works on the standard Brayton Cycle, where the packed air is blended with fuel, and copied under steady weight conditions. The subsequent hot gas is permitted to extend through a turbine to perform work.

3.1.4 Gas Turbine Performance:

Certain climatic conditions critically affect any given gas turbine's accessible power:

a) **Ambient temperature:** As this ascent, a gas turbine may swallow a similar volume of air, yet that air will weigh less with expanding climatic temperature. Less air mass means less fuel mass is required to be touched off with that air and considerably lower power created.

b) **Altitude:** Increasing elevation implies bring down thickness air, so that is, in turn, diminishes power created by the turbine.

c) **Humidity:** Water vapor is less thick than air, so more water vapor in each volume implies less weight of that air than if it had less water vapor. The impact is the same as with the two above elements.

The subject of performance optimization is an immense one which would incorporate a few subtopics. Channel cooling and water/steam infusion for power enlargement can be techniques which are utilized to supplement power "lost" by elements, for example, high ambient temperatures, and high elevation.

Contingent upon how one characterized performance optimization, the term could incorporate cycle modifications and emotionally supportive networks that are outside to the gas turbine center. A few cases are:

- Cycle modifications.
- Engine condition observing frameworks.
- Life cycle counters/assessment

3.2 Heat Recovery Steam Generator (HRSG):

The heat recovery steam generator (HRSG) gives the thermodynamic connection between the gas turbines and steam turbines in a combined cycle power plant. Each HRSG arrangement is exclusively designed to meet your coveted working adaptability and execution necessities.

A heat recovery steam generator (HRSG) is an energy recovery heat exchanger that recuperates heat from a hot gas stream. It produces steam that can be utilized as a part of a procedure (cogeneration) or used to drive a steam turbine (combined cycle).

HRSGs comprise four major components**: the economizer, evaporator, superheater & water preheater**. Here another component called **desuperheater** is also installed to extract as much heat from the gas to convert water to steam as much as possible.

In view of the stream of fumes gases, HRSGs are arranged vertically, and level composes. In **level kind HRSGs**, fumes gas streams on a level plane over vertical tubes while in **vertical sort HRSGs**, fumes gas stream vertically finished flat tubes. Considering weight levels, HRSGs can be ordered into single weight and multi-weight**. Single weight HRSGs** has just a single steam drum, and steam is created at single weight level though **multi-weight HRSGs** utilizes two (twofold weight) or three (triple weight) steam drums. All things considered, triple weight HRSGs comprises three areas: a **LP (low weight) segment**, **IP (moderate weight)** segment, and a **HP (high weight) segment**. Each area has a steam drum and an evaporator segment where water is changed over to steam. This steam at that point goes through superheaters to raise the temperature past the immersion point.

3.3 Co-generation Cycle:

Cogeneration via combined heat and power (CHP) is the concurrent generation of electricity along with the recovery and utilization of heat. This process represents a remarkably efficient method of energy conversion, capable of realizing primary energy savings of around 40% when compared to the independent acquisition of electricity from the national grid and the use of a gas boiler for on-site heating.

Combined heat and power (CHP) plants are usually situated in close proximity to end-users, thereby minimizing transportation and distribution losses. This proximity enhances the efficiency of the electricity transmission and distribution network, especially for power users who prioritize security of supply when selecting power production equipment. In regions with ample gas resources, gas-based cogeneration systems serve as optimal captive power plants, strategically located at the site of use.

3.4 Process Flow Diagram

The process flow diagram of our project is as follows:

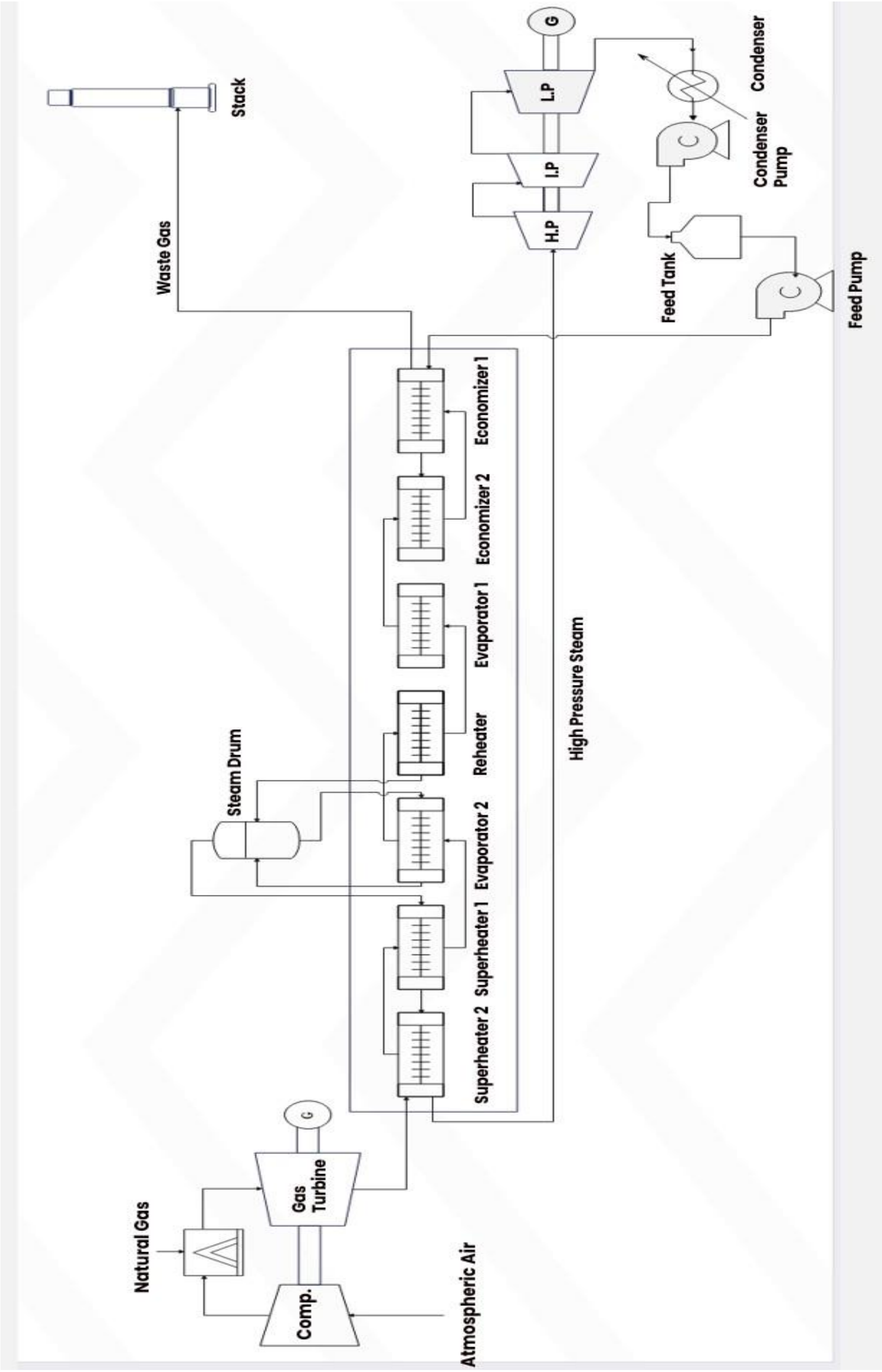


Figure 3.1 Process Flow Diagram

CHAPTER 4

MATERIAL BALANCE

4.1 Material Balance on Compressor:

There is no change in the mass of the inlet and outlet streams in the compressor. This is because it follows the following principles:

- **Conservation of Mass:**

The total mass of a closed system remains constant. The air enters the compressor, compressed to a high pressure and then discharged without any change in the mass.

- **Material Integrity:**

The compressor is made with such a material that can withstand the operating conditions such as pressure and temperature changes in it without undergoing a change in the chemical composition.

4.1.1 Balance:

Mass flowrate of the Inlet Air = 20700 kg/hr (Given)

So,

Mass flowrate of Outlet Air = Mass flowrate of Inlet Air = 20700 kg/hr

4.1.2 Calculation of Flowrates (Fuel Gas):

Given:

Table 4.1 Fuel Gas Composition

FUEL GAS COMPOSITION	
Components	**Percentage**

Methane	76.97%
Ethane	0.09%
Hexane	0.02%
CO2	0.39%
N2	22.53%

Table 4.2 Fuel Gas Properties

Average Molecular Weight Mw (kg/kgmol)	18.84
Ideal Gas Constant, R (m3 kgf/cm2 K mol)	0.000084784
Volume, V (m3/hr)	7842.34
Pressure, P (kgf/cm2)	1.033
Temperature,T (K)	273

Molar Flow of Fuel Gas (N) $= \frac{P \times V}{R \times T} = \frac{1.033 \times 7842.34}{0.000084784 \times 273} = \mathbf{350001.12\ kgmol / hr}$

Converting to kg mol:

$$\frac{350001.12}{1000} = \mathbf{350\ kgmol / hr}$$

Mass Flow of Fuel Gas = N x M_w = 350 x 18.84 = 6594.02 kg /hr

4.2 Material Balance on Combustion Chamber:

The following reactions occur in the turbine:

$$\mathbf{CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O} \qquad \text{.........} \ \mathbf{(1)}$$

$$C_2H_6 + \frac{7}{2}O_2 \longrightarrow 2CO_2 + 3\,H_2O \qquad \text{......... (2)}$$

$$C_6H_{14} + \frac{19}{2}O_2 \longrightarrow 6CO_2 + 7\,H_2O \qquad \text{......... (3)}$$

$$CH_4 + \frac{3}{2}O_2 \longrightarrow CO + 2\,H_2O \qquad \text{......... (4)}$$

All reactions are of complete combustion of hydrocarbons to form carbon dioxide and water except for the reaction **(4)**, where the methane is undergoing incomplete combustion to form carbon monoxide and water. This incomplete combustion starts after 88% of complete combustion is achieved in reaction **(1).**

We know the fuel gas composition and air composition as,

Table 4.3 Fuel Gas Composition (2)

FUEL GAS COMPOSITION	
Components	**Percentage**
Methane	76.97%
Ethane	0.09%
Hexane	0.02%
CO2	0.39%
N2	22.53%

Table 4.4 Air Composition

AIR COMPOSITION	
Components	**Percentage**
N2	79%
O2	21%

Basis:

350 kgmol/hr of fuel gas

All calculations are done by using the simple stoichiometric molecular analysis.

4.2.1 Oxygen (O_2) Required

Reaction 1:

O_2 required = $\frac{76.97}{100}$ x 350 x 2 = **538.79 kgmol**

88 % combustion efficiency = 538.79 × 0.88 = **474.14 kgmol**

Reaction 2:

O_2 required = $\frac{0.09}{100}$ x 350 x $\frac{7}{2}$ = **1.10 kgmol**

Reaction 3:

O_2 required = $\frac{0.02}{100}$ x 350 x $\frac{19}{2}$ = **0.67 kgmol**

Reaction 4:

$$O_2 \text{ required} = \frac{before\ 88\%\ combustion - after\ 88\%\ combustio}{\text{reactant oxygen}} \times \frac{3}{2}$$

$$= \frac{538.79 - 474.14}{2} \times \frac{3}{2}$$

= 48.49 kgmol

Total O_2 needed for combustion = 524.4 kgmol

4.2.2 Carbon dioxide (CO_2) Produced

Reaction 1:

CO_2 produced = $\frac{76.97}{100}$ x 350 x 1 = **269.40 kgmol**

After 88 % combustion efficiency = 269.40 × 0.88 = **237.07 kgmol**

Reaction 2:

CO_2 produced = $\frac{0.09}{100}$ x 350 x 2 = **0.63 kgmol**

Reaction 3:

CO_2 produced = $\frac{0.02}{100}$ x 350 x 6 = **0.42 kgmol**

Reaction 4:

No CO_2 is produced here as it is an incomplete combustion reaction.

Total CO_2 needed for combustion = 238.12 kgmol

4.2.3 Water (H_2O) Produced

Reaction 1:

H_2O produced = $\frac{76.97}{100}$ x 350 x 2 = 538.79 kgmol

After 88 % combustion efficiency = 538.79 × 0.88 = **474.14 kgmol**

Reaction 2:

H_2O produced = $\frac{0.09}{100}$ x 350 x 3 = **0.95 kgmol**

Reaction 3:

H_2O produced = $\frac{0.02}{100}$ x 350 x 7 = **0.49 kgmol**

Reaction 4:

$$H_2O \text{ produced} = \frac{before\ 88\%\ combustion - after\ 88\%\ combustio}{\text{reactant water}} \times 2$$

$$= \frac{538.79 - 474.14}{2} \times 2$$

= **64.66 kgmol**

Total H_2O needed for combustion = 540.23 kgmol

4.2.4 Air Needed

Theoretical O_2 = **524.40 kgmol** (already calculated)

Excess Air = 14.5% (given)

Formula for excess air is:

$$\text{Excess Air} = \frac{\text{O2 Actually Needed} - \text{O2 Theoretically Needed}}{\text{O2 Theoretically Needed}}$$

By rearranging this equation,

O_2 actually needed = (14.5% x 524.40) + 524.40 = **600.438 kgmol**

We use another formula to find the moles of air needed,

Air Needed x O_2 (%) in Air = O_2 Actually Needed

By rearranging,

$$\textbf{Air needed} = \frac{\mathbf{600.43}}{\mathbf{14.5\%}} = \textbf{2859.20 kgmol}$$

4.2.5 Nitrogen (N_2) Needed

N_2 in fuel gas = N_2 composition in fuel gas x Molar flow of fuel gas

= 22.53% x 350

= 78.86 kgmol

N_2 in air = N_2 composition in air x Air needed

= 79% x 2859.20

= 2258.77 kgmol

Total = N_2 in fuel gas + N_2 in air

= 78.86 + 2258.77

= 2337.63 kgmol

4.2.6 Carbon dioxide (CO_2) Needed

CO_2 in fuel gas = CO_2 composition in fuel gas x Molar flow of fuel gas

= 0.39% x 350

= `1.37 kgmol

In the air there is no carbon dioxide so its value is zero there.

Total = CO_2 in fuel gas + CO_2 in air

= 1.37 + 0

= 1.37 kgmol

4.2.7 Carbon Monoxide (CO) Produced

From stoichiometric reaction (4) we can see that,
1.5 kgmol of O_2 will provide 1 kgmol of CO.
So if we have 48.49 kgmol of O_2 (already calculated) then,

Moles of CO produced = $\frac{48.49}{1.5}$ = **32.328 kg mol**

4.2.8 Methane (CH_4) Needed

From stoichiometric reaction (1) we can see that,
2 kgmol of O_2 will react with 1 kgmol of CH_4.
So, if we have 538.79 kgmol of O_2 (already calculated) then,
Moles of CH_4 reacted = $\frac{538.79}{2}$ = **269.396 kg mol**

4.2.9 Ethane (C_2H_6) Needed

From stoichiometric reaction (2) we can see that,
3.5 kgmol of O_2 will react with 1 kgmol of C_2H_6.
So, if we have 1.10 kgmol of O_2 (already calculated) then,

Moles of CH_4 reacted = $\frac{1.10}{3.5}$ = **0.315 kg mol**

4.2.10 Hexane (C_6H_{14}) Needed

From stoichiometric reaction (3) we can see that,
9.5 kgmol of O_2 will react with 1 kgmol of C_2H_6.
So, if we have 0.67 kgmol of O_2 (already calculated) then,

Moles of CH_4 reacted = $\frac{0.67}{9.5}$ = **0.070 kg mol**

4.2.11 Overall Material Balance

Simply multiplying the molar units by the molecular weights, we can calculate the amounts of components in mass units.

4.2.11.1 Inlet Streams:

Fuel Gas:

CH_4 = 269.396 × 16 = 4310.33 kg
N_2 = 78.86 ×28 = 2207.95 kg
CO_2 = 1.37 ×44 = 60.06 kg
C_2H_6 = 0.315 × 30 = 9.45 kg
C_6H_{14} = 0.070 × 86 = 6.02 kg

Total Fuel Gas = 6593.81 kg

Air:

O_2 = 600.43 x 32 = 19213.85 kg
N_2 = 2258.77 x 28 = 63245.59 kg

Total Air = 82459.44 kg

Total Inlet = 89057.85 kg

4.2.11.2 Outlet Stream:

O_2 = (600.43 – 524.4) x 32 = 2433.20 kg

N_2 = 2337.63 x 28 = 65453.54 kg

CO_2 = 238.12 x 44 = 10477.21 kg

CO = 32.328 x 30 = 969.83 kg

H_2O = 540.23 x 18 = 9724.08 kg

Total Outlet = 89057.85 kg

4.3 Material Balance on Gas Turbine:

The mass entering and leaving the gas turbine would be constant due to the same principles already discussed in the compressor section.

Conservation of Mass:

Total mass of a closed system remains constant. The outlet stream from the combustion chamber enters the gas turbine, does work on the blades to generate electricity and then discharges the exhaust stream without any change in the mass.

Material Integrity:

The turbine itself does not undergo any change in material during the expansion process. The materials used in the construction of the turbine are designed to withstand the high temperatures and pressures associated with the expansion of the fluid without undergoing a change in their chemical composition.

4.3.1 Balance:

Combustion Exhaust = Sum of all the components in the Outlet Stream of Combustion Chamber

= 3225.70 kgmol (89057.85 kg)

So,

Combustion Exhaust = Gas Turbine Outlet = 3225.70 kgmol (89057.85 kg)

4.4 Material Balance on HRSG (Heat Recovery Steam Generator):

In the HRSG, the composition of each component is provided in the table below:

Table 4.5 Flue Gas / Waste Heat Composition

Components	Composition
O_2	0.1303
CO_2	0.0318
CO	0.0043
H_2O	0.0716
N_2	0.7621
TOTAL	**1.0000**

Multiplying each composition with the total molar flowrate of the stream entering the HRSG gives us the individual molar flowrates which can then be converted to mass flowrates easily.

Molar Flow of O_2 = 0.1303 x 3225.70 = 420.18 kgmol

= 420.18 x 32 = **2433.20 kg**

Molar Flow of CO_2 = 0.0318 x 3225.70 = 102.43 kgmol

= 102.43 x 44 = **10477.21 kg**

Molar Flow of CO = 0.0043 x 3225.70 = 13.83 kgmol

= 13.83 x 30 = **969.83 kg**

Molar Flow of H_2O = 0.0716 x 3225.70 = 231.07 kgmol

= 231.07 x 18 = **9724.08 kg**

Molar Flow of N_2 = 0.7621 x 3225.70 = 2458.19 kgmol

= 2458.19 x 28 = **65453.54 kg**

Total Molar Flowrate = 3225.70 kgmol (89057.85 kg)

The molar flowrate of the water entering the HRSG from the opposite direction is 1480 kgmol (26640 kg).

There is no change in the mass entering the HRSG and mass leaving the HRSG as it is closed system and law of conservation of mass is applied. In heat exchanger only the heat is exchanged between two fluids there is no change in mass. So,

Total Inlet = Water In + Turbine Exhaust = 115697.848 kg

Total Outlet = Waste Steam Out + Waste Heat Leaving = 115697.848 kg

4.5 Material Balance on Steam Turbine:

Similarly, as in the case of gas turbine, in steam turbine as well, there cannot be any material balance applied as there is no change in the mass in the inlet and outlet streams. So, in all three sections of the steam turbine (High Pressure, Low Pressure and Intermediate Pressure), the flowrates are equal,

HP Inlet = HP Outlet = 26670 kg

IP Inlet = IP Outlet = 26670 kg

LP Inlet = LP Outlet = 26670 kg

CHAPTER 5

ENERGY BALANCE

5.1 Energy Balance on Compressor:

Overall Energy Balance Equation:

Three stages are taken here to calculate the work required by the compressor to compress the air from 1 bar to 30 bar. In these three stages, pressure ratio is taken as equivalent to 3.1 bar.

Equation for calculating the work required for the compressor:

$$-\boldsymbol{W} = \boldsymbol{ZRT}\frac{\boldsymbol{n}}{\boldsymbol{n}-\mathbf{1}}\left[(\boldsymbol{P_2}/\boldsymbol{P_1})^{\frac{(\boldsymbol{n}-\mathbf{1})}{\boldsymbol{n}}} - \mathbf{1}\right]$$

Where,

W is the work Required, kW

Z is the compressibility factor

R is the general gas constant, $\frac{kJ}{kmol*K}$

T is the inlet Temperature, K

n is the polytropic constant

P2 is the outlet pressure bar.

P1 is the outlet pressure, bar.

Table 5.1 Energy Balance on Compressor stage 1

STAGE 1				
Compressibility factor, Z	0.9995			
General Gas Constant, R (kJ/kmol*K)	8.314			
Heat Capacity Ratio, γ	1.401		**Pressure Ratio, P2/P1**	3.11
Polytropic Efficiency, Ep	0.76		**Pressure Ratio Power, (γ −1)/ γ**	0.217530335
Inlet Temperature, T1 (K)	298		**n/(n-1)**	4.597059982
Inlet Pressure, P1 (bar)	1		**Z*R*T1 (kJ/kmol)**	2476.333214
Outlet Pressure, P2 (bar)	3.11		**Molar Flow (kmol/hr)**	7175
Polytropic Temperature Exponent, m	0.217530335			
Polytropic Exponent, n	1.278004816			
Polytropic Work, W (kJ/kmol)	3186.819812			
Polytropic Work, W (kJ/hr)	22865432.15			
Polytropic Work, W (kJ/s)	6351.508931			

Actual Work Required = -8357.248593 kW (-8.357248593 MW)

Table 5.2 Energy Balance on Compressor stage 2

STAGE 2			
Compressibility factor, Z	0.9985		

General Gas Constant, R (kJ/kmol*K)	8.314			
Heat Capacity Ratio, γ	1.404		**Pressure Ratio, P2/P1**	3.118971061
Polytropic Efficiency, Ep	76%		**Pressure Ratio Power, $(n-1)/n$**	0.218689459
Inlet Temperature, T1 (K)	308		**n/(n-1)**	4.572694112
Inlet Pressure, P1 (bar)	3.11		**Z*R*T1 (kJ/kmol)**	2556.870932
Outlet Pressure, P2 (bar)	9.7		**Molar Flow (kmol/hr)**	7175
Polytropic Temperature Exponent, m	0.218689459			
Polytropic Exponent, n	1.279900817			
Polytropic Work, W (kJ/kmol)	3302.160367			
Polytropic Work, W (kJ/hr)	23693000.64			
Polytropic Work, W (kJ/s)	6581.389066			

Actual Work Required = -8659.722455 kW (-8.659722455 MW)

Table 5.3 Energy Balance on Compressor stage 3

STAGE 3				
Compressibility factor, Z	0.9955			
General Gas Constant, R (kJ/kmol*K)	8.314			
Heat Capacity Ratio, γ	1.416		**Pressure Ratio, P2/P1**	3.092783505
Polytropic Efficiency, Ep	76%		**Pressure Ratio Power, $(n-1)/n$**	0.223276836

Inlet Temperature, T1 (K)	308		**n/(n-1)**	4.478744939
Inlet Pressure, P1 (bar)	9.7		**Z*R*T1 (kJ/kmol)**	2549.188796
Outlet Pressure, P2 (bar)	30		**Molar Flow (kmol/hr)**	7175
Polytropic Temperature Exponent, m	0.223276836			
Polytropic Exponent, n	1.287459994			
Polytropic Work, W (kJ/kmol)	3273.517714			
Polytropic Work, W (kJ/hr)	23487489.6			
Polytropic Work, W (kJ/s)	6524.302667			

Actual Work Required (kW) = -8584.608772 kW (-8.584608772 MW)

5.2 Energy Balance on Combustion Chamber:

In Combustion Chamber, amount of heat is calculated by the following formula:

$$\mathbf{Q = mC_p\Delta T}$$

Where,

Q is the amount of heat

m is the mass flow rate

Cp is the specific Heat Capacity

ΔT change in temperature.

Table 5.4 Energy Balance on Combustion Chamber

INLET	AIR		FUEL
Cp (kJ/kg*C)	1.065		1.884

Tin (C)	188.3		56.2
min = mout (kg)	2.07E+05		6606
Q (J)	36000301.5		388305.9648
IN CHAMBER		**PRODUCTION**	
Hrxn (kJ/kgmol)		-643.98	
n (kgmoles)		350	

5.2.1 Amount of heat at the inlet of combustion chamber:

$$Q_{in} = Q_{air} + Q_{fuel}$$

$$Q_{in} = 36000301.5 + 388305.9648$$

$$\mathbf{Q_{in} = 36388607.46\ J}$$

$$Q_{in} = \frac{36388607.46}{10^6}$$

$$\mathbf{Q_{in} = 36.389\ MJ}$$

5.2.2 Amount of heat produced during combustion chamber:

$$Q_{produced} = H_{rxn} * n$$

$$Q_{produced} = -643.98 * 350$$

$$\mathbf{Q_{produced} = -225393\ kJ\ (-225.393\ MJ)}$$

Table 5.5 Properties of Exhaust gas at outlet of combustion chamber

OUTLET	**EXHAUST GAS**
Cp (kJ/kg*C)	1.254
T (C)	1003.00
m (kg/hr)	2.14E+05

5.2.3 Amount of heat at the outlet of Combustion Chamber:

$$Q_{out} = 2.14E + 05 * 1.254 * (1003 - 25)$$

$$\mathbf{Q_{out}}\ (J) = \mathbf{2.62 * 10^8 J\ (261.96\ MJ)}$$

5.2.4 Overall material balance on Combustion Chamber:

$$Q_{in} - Q_{produced} = Q_{out}$$

$$\mathbf{261\ MJ = 261\ MJ}$$

5.3 Energy Balance on Gas Turbine:

Equation for calculating the work produced by the turbine:

$$-W = ZRT\ \frac{n}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1\right]$$

Table 5.6 Energy Balance on Gas Turbine

Work Produced by Expansion				
Compressibility factor, Z	1.000			
General Gas Constant, R (kJ/kmol*K)	8.314			
Heat Capacity Ratio, γ	1.319		**Pressure Ratio, P2/P1**	0.040375123
Polytropic Efficiency, Ep	0.750		**Pressure Ratio Power, (□−1)/□**	0.181387415
Inlet Temperature, T1 (K)	1003.000		**n/(n-1)**	5.513061651
Inlet Pressure, P1 (bar)	1.013		**Z*R*T1 (kJ/kmol)**	8338.942

Outlet Pressure, P2 (bar)	0.041		**Molar Flow (kmol/hr)**	7541
Polytropic Temperature Exponent, m	0.181			
Polytropic Exponent, n	1.222			
Polytropic Work, W (kJ/kmol)	-20288.644			
Polytropic Work, W (kJ/hr)	-152996662.236			
Polytropic Work, W (kJ/s)	-42499.073			

Actual Work Produced (kW) = 31874.30463 kW (31.87430463 MW)

5.4 Energy Balance on Heat Recovery Steam Generator (HRSG):

HRSG consists of four heat exchangers, Economizer, Evaporator, Super heater, and de-superheater. HRSG utilizes the heat from the exhaust gases and make steam from the water. Total amount of heat calculated at both the inlet and outlet of shell and tube is calculated by the following equation:

$$\boldsymbol{Q = mC_p\Delta T}$$

Where,

Q is the amount of heat

m is the mass flow rate

Cp is the specific Heat Capacity

ΔT change in temperature

Table 5.7 Energy Balance on Economizer

ECONOMIZER					
	Shell Side (Waste Heat)			**Tube Side (Water)**	
	In	**Out**		**In**	**Out**
Vapor	1.00	1.00		0.00	0.00
Temp (C)	139.40	94.01		35.04	124.40
Pressure (bar)	0.04	0.04		5.00	5.000
Mass Flow (kg/hr)	213605.65	213605.65		26665.36	26665.36
Cp (kJ/kgC)	1.078	1.067		4.31	4.47
Q (kJ/hr)	**2888.47**			**-2888.47**	
0.00					

Table 5.8 Energy Balance on Evaporator

EVAPORATOR					
	Shell Side (Waste Heat)			**Tube Side (Water)**	
	In	**Out**		**In**	**Out**
Vapor	1.00	1.00		0.00	0.00
Temp (C)	152.80	139.40		124.40	150.00
Pressure (bar)	0.04	0.04		5.00	5.00
Mass Flow (kg/hr)	213605.65	213605.65		26665.36	26665.36
Cp (kJ/kgC)	1.081	1.078		4.47	4.57
Q (kJ/hr)	**858.30**			**-858.30**	
0.00					

Table 5.9 Energy Balance on Superheater

SUPER-HEATER					
	Shell Side (Waste Heat)			**Tube Side (Water)**	
	In	**Out**		**In**	**Out**
Vapor	1.00	1.00		0.00	1.00
Temp (C)	428.00	152.80		150.00	310.00
Pressure (bar)	0.04	0.04		5.00	5.00
Mass Flow (kg/hr)	213605.65	213605.65		26665.36	26665.36
Cp (kJ/kgC)	1.146	1.081		4.571	2.043
Q (kJ/hr)	**-42690025.42**			**42690025.42**	
0.00					

Table 5.10 Energy Balance on De-Superheater

DE-SUPERHEATER					
	Shell Side (Waste Heat)			**Tube Side (Water)**	
	In	**Out**		**In**	**Out**
Vapor	1.00	1.00		1.00	1.00
Temp (C)	485.00	428.00		202.00	460.00
Pressure (bar)	0.03	0.03		3.07	3.07
Mass Flow (kg/hr)	213605.65	213605.65		26665.36	26665.36
Cp (kJ/kgC)	1.158	1.146		1.959	2.122
Q (kJ/hr)	**3899.43**			**-3899.43**	
0.00					

5.5 Energy Balance on Pump:

Boiler Feed Water (BFW) from the feed tank is pumped through the centrifugal pump and is sent to the HRSG, for the utilization of energy(heat).

Mechanical work consumed by the pump is calculated by the **BERNOULLIS EQUATION**:

$$\eta Q_{Pump} = \dot{m}\ (\Delta Z + \frac{\Delta P}{\rho g} + \Delta\frac{v^2}{2g}) + Q_{losses}$$

$$\eta Q_{Pump} = \dot{m}\ (\frac{\Delta P}{\rho})$$

As the head is increased in the pump so neglecting potential and kinetic energy terms, we get this.

$$Q_{Pump} = \frac{\dot{m}}{\eta}\ (\frac{\Delta P}{\rho})$$

Table 5.11 Energy Balance on Pump

	IN	OUT
Temperature (C)	35.163	35.04
Specific Enthalpy (kJ/kg)	-15886.65	-15886.65
Pressure (N/m2)	101300	500000
Density (kg/m^3)	999.8	999.8
Mass Flow Rate (kg/h)	2.67E+04	2.67E+04
Cp (kJ/kg*C)	4.314	4.314
Adiabatic Efficiency (η)	75%	
Pump Duty (m3kPa/hr)	-14180608.12	
Pump Duty kW	-3.94	
Q (kJ/s)	324.80	320.87

5.5.1 Overall Energy Balance on Pump:

$$\text{Win} + \text{Qin} = \text{Qout}$$

$$-3.94 + 324.80 = 320.87$$

$$\mathbf{320.87 = 320.87} \ \left(\frac{\mathbf{kJ}}{\mathbf{s}}\right)$$

5.6 Energy Balance on Steam Turbine:

5.6.1 HP Steam Turbine:

High Pressure steam turbine takes the high-pressure steam from the super heater and return the remaining exhaust steam to the de-super heater to utilize the heat from the exhaust gases.

Equation for calculating the work produced by the turbine:

$$-\boldsymbol{W} = \boldsymbol{ZRT}\frac{\boldsymbol{n}}{\boldsymbol{n-1}}\left[(\boldsymbol{P_2/P_1})^{\frac{(\boldsymbol{n-1})}{\boldsymbol{n}}} - \mathbf{1}\right]$$

Table 5.12 Energy Balance on HP Steam Turbine

HP STEAM TURBINE				
Compressibility factor, Z	0.9903			
General Gas Constant, R (kJ/kmol*K)	8.314			
Heat Capacity Ratio, γ	1.304		**Pressure Ratio, P2/P1**	0.3032
Polytropic Efficiency, Ep	65%		**Pressure Ratio Power, (□−1)/□**	0.151533742
Inlet Temperature, T1 (K)	583		**n/(n-1)**	6.599190283
Inlet Pressure, P1 (bar)	5		**Z*R*T1 (kJ/kmol)**	4800.045499
Outlet Pressure, P2 (bar)	1.516		**Molar Flow (kmol/hr)**	1480
Polytropic Temperature Exponent, m	0.151533742			

Polytropic Exponent, n	1.178597252		
Polytropic Work, W (kJ/kmol)	-5240.124621		
Polytropic Work, W (kJ/hr)	-7755384.439		
Polytropic Work, W (kJ/s)	-2154.273455		

Actual Work Produced (kW) = 1400.278 kW (1.4002 MW)

5.6.2 IP Steam Turbine:

Intermediate Pressure steam turbine takes the IP steam from the De-superheater and sends the exhaust steam to the low-pressure steam turbine.

Equation for calculating the work produced by the turbine:

$$-W = ZRT\frac{n}{n-1}\left[(P_2/P_1)^{\frac{(n-1)}{n}} - 1\right]$$

Table 5.13 Energy Balance on IP Steam Turbine

IP STEAM TURBINE				
Compressibility factor, Z	0.9983			
General Gas Constant, R (kJ/kmol*K)	8.314			
Heat Capacity Ratio, γ	1.282		**Pressure Ratio, P2/P1**	0.447229551
Polytropic Efficiency, Ep	65%		**Pressure Ratio Power, (▯−1)/▯**	0.142979719
Inlet Temperature, T1 (K)	733		**n/(n-1)**	6.993998909
Inlet Pressure, P1 (bar)	1.516		**Z*R*T1 (kJ/kmol)**	6083.801925

Outlet Pressure, P2 (bar)	0.678		**Molar Flow (kmol/hr)**	1480
Polytropic Temperature Exponent, m	0.142979719			
Polytropic Exponent, n	1.166833531			
Polytropic Work, W (kJ/kmol)	-4624.406752			
Polytropic Work, W (kJ/hr)	-6844121.994			
Polytropic Work, W (kJ/s)	-1901.144998			

Actual Work Produced (kW) = 1235.744 kW (1.235744 MW)

5.6.3 LP Steam Turbine:

Low Pressure steam turbine takes the exhaust steam from the IP steam turbine and return the exhaust to steam to the Condenser.

Equation for calculating the work produced by the turbine:

$$-W = ZRT\frac{n}{n-1}\left[(P_2/P_1)^{\frac{(n-1)}{n}} - 1\right]$$

Table 5.14 Energy Balance on LP Steam Turbine

LP STEAM TURBINE				
Compressibility factor, Z	0.9985			
General Gas Constant, R (kJ/kmol*K)	8.314			
Heat Capacity Ratio, γ	1.29		**Pressure Ratio, P2/P1**	0.47640118

Polytropic Efficiency, Ep	65%		**Pressure Ratio Power, (□−1)/□**	0.146124031
Inlet Temperature, T1 (K)	643		**n/(n-1)**	6.843501326
Inlet Pressure, P1 (bar)	0.678		**Z*R*T1 (kJ/kmol)**	5337.883147
Outlet Pressure, P2 (bar)	0.323		**Molar Flow (kmol/hr)**	1480
Polytropic Temperature Exponent, m	0.146124031			
Polytropic Exponent, n	1.171130277			
Polytropic Work, W (kJ/kmol)	-3751.126687			
Polytropic Work, W (kJ/hr)	-5551667.496			
Polytropic Work, W (kJ/s)	-1542.12986			

Actual Work Produced (kW) = 1002.3844 kW (1.0024 MW)

5.7 Energy Balance on Condenser:

Total amount of heat calculated at the inlet and outlet of Condenser is calculated by the following equation:

$$\mathbf{Q = mC_p\Delta T}$$

Table 5.15 Energy Balance on Condenser

	IN	**OUT**
Mass Flow, m (kg/hr)	26665.36	26665.36
Cp (kJ/kg*C)	2.006	4.314

T (°C)	295	35
Heat of Vaporization, (kcal/kg)	561.9	544.1
Heat of Vaporization, (kJ/kg)	2350.9896	2276.5144
Heat Liberated (kJ/hr)	8.36E+07	
Heat Liberated (kJ/s)	23223.69	
Q (kJ/s)	23543.23	319.5398973

5.7.1 Overall Energy Balance on Condenser:

$$\text{Qin} = \text{Qout} + \text{Heat Liberated}$$

$$23543.23 = 23223.69 + 319.5$$

$$\mathbf{23543.23 = 23543.23 \quad (\frac{kJ}{s})}$$

CHAPTER 6

EQUIPMENT DESIGN

6.1 Heat Recovery Steam Generator

Tube Material is Carbon Steel

Fin Material is Aluminum.

6.1.1 Economizer 1:

Assumptions (Schedule No. 40)

Tube Outer Diameter (TOD) = 26.67 mm

Tube Inner Diameter (TID) = 23.80 mm

Thickness of Tube = 2.87 mm

Fin Outer Diameter (FOD) = 45.30 mm

Thickness of Fin (t_f) = 0.12 mm

Number of fins per unit length (N_f) = 612

Effective Length of tube (L) = 1.72 m

Length of heat exchanger tube sheet (W) = 3.21 m

Distance b/w fin ends = 0.857 cm

Number of Passes (Np) = 6

6.1.1.1 Fin Side Calculations

- **Fin Area / unit tube length:**

$$A_f = (\pi/4)\ (FOD^2 - TOD^2) \times 2 \times N_f$$

$A_f = 1.29\ m^2/m$ tube length

- **Bare Tube Area:**

$A_b = (\pi \times TOD) - \pi \times TOD \times t_f \times N_f$

$A_b = 0.078\ m^2/m$ tube length

- **Projected Perimeter:**

$P_e = 2 \times (FOD\text{-}TOD) \times N_f + 2 \times (1 - t_f \times N_f)$

$P_e = 24.656\ m/m$ tube length

- **Equivalent Diameter:**

$D_e = 2 \times (A_f + A_b) / (\pi \times P_e)$

$D_e = 0.035$

- **Fin Side Side Flow Area:**

$a_s = (LW) - (N_p \times TOD \times L) - (N_p \times t_f \times n_f \times L \times (FOD - TOD))$

$a_s = 4.02\ m^2$

- **Fin Side Mass Velocity:**

$m^{\cdot} = 25.4$ kg/s (given)

$G_s = m^{\cdot} / N_f$

$G_s = 6.32$ kg/s m^2

- **Fin Side Reynolds Number:**

$\mu = 3.37E\text{-}05$ kg /m.s (literature)

$R_e = D_e \times (G_s / \mu)$

$R_e = 6616.21$

- **Fin Side Prandtl Number:**

$C_p = 1278$ J/kg.K , $k = 0.0342$ W/m.K (literature)

$P_r = (\mu\ C_p) / k$

$P_r = 1.26$

- **Number of tubes in a bundle:**

N_t = (L / TOD) + 2 + (Distance b/w fin ends)

$N_t = 31$

- **Factor of heat transfer coefficient:**

$J_{ha} = 0.0852072 \times Re^{0.7324}$

$J_{ha} = 53.54$

- **Clean heat transfer coefficient:**

$h_f = J_{ha} (k / D_e) \times P_r^{1/3}$

$h_f = 56.04\ W / m^2K$

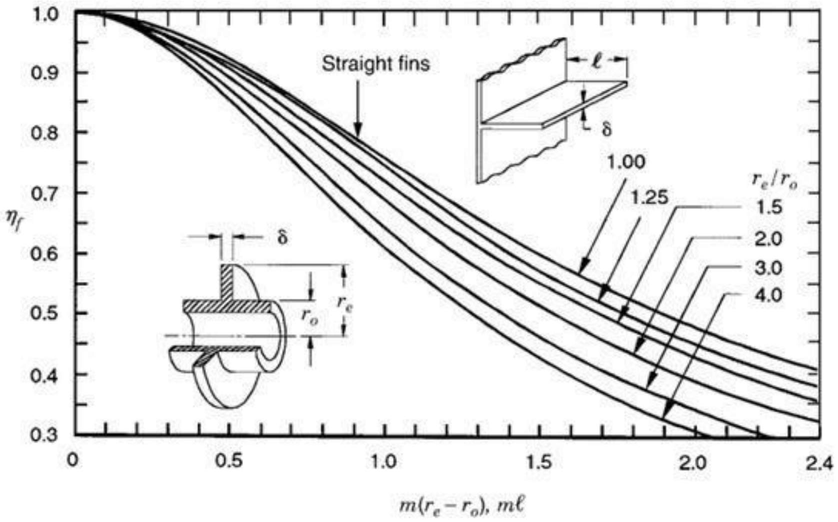


Figure 6.1 Fin Efficiency of Economizer 1

- **Fin Efficiency:**

r_e = radius of finned tube = 45.30 / 2 = 22.65 mm

r_b = radius of bare tube = 26.67 / 2 = 13.33 mm

k_f = thermal conductivity of aluminum = 237 W/m.K (literature)

$\eta = \tanh m \times (r_e - r_b) / m \times (r_e - r_b)$

$m = (2 \times h_f / k_f \times t_f)^{1/2}$

$\eta = 0.90$

- **Dirty fin side heat transfer coefficient:**

$h_{ft} = (\eta \text{ x } A_b + A_f)\text{x } (h_f / \pi) \text{ x TID}$

$h_f = 927.38 \text{ W / m}^2\text{K}$

6.1.1.2 Tube Side Calculations

- **Inner Tube Area:**

$a_t = N_t \text{ x } (\pi/4) (\text{TID}^2)$

$a_t = 0.014 \text{ m}^2$

- **Tube Mass Velocity:**

$\dot{m}_w = 7.408$ kg/s (given)

$G_t = \dot{m}_w \text{ x } a_t$

$G_t = 534.72 \text{ kg / s m}^2$

- **Tube Velocity:**

$\rho = 1000 \text{ kg/m}^3$ (literature)

$u_t = G_t / \rho$

$u_t = 0.53 \text{ m / s}$

- **Tube Side Reynolds Number:**

$\mu_w = 7.14 \text{ x } 10^{-4}$ kg/m.s (literature)

$R_{et} = (\text{TID x } G_t) / \mu_w$

$R_{et} = 17833.98$

- **Tube Side Prandtl Number:**

$C_{pw} = 4180$ W/m.K , $k_w = 0.0635$ W/m.K (literature)

$P_{rt} = (\mu_w \times C_{pw}) / k_w$

$P_{rt} = 46.97$

- **Internal Heat Transfer Coefficient:**

$h_i = (0.023 \times R_{et}^{0.8} \times P_{rt}^{0.33} \times k_w) / TID$

$h_i = 550.35\ W / m^2 \times K$

- **Fouling Factor Coefficient:**

$h_{id} = 4487\ W / m^2 \times K$

- **Overall Heat Transfer Coefficient:**

$1/U = (1/h_{ft}) + (1/h_i) + (1/h_{id})$

$U = 320.70\ W/m^2\ K$

6.1.1.3 Area Calculations and Total Tubes

First, we will calculate the Logarithmic Mean Temperature Difference (LMTD):

Inlet Hot Stream Temperature = 182.3 C

Outlet Hot Stream Temperature = 160.2 C

Inlet Cold Stream Temperature = 35.44 C

Outlet Cold Stream Temperature = 80 C

$$\Delta T_{lm} = \frac{(T_{Hin} - T_{Cout}) - (T_{Hout} - T_{Cin})}{\ln \dfrac{(T_{Hin} - T_{Cout})}{(T_{Hout} - T_{Cin})}}$$

$\Delta T_{lm} = 113.16$ C

By using the graph below we find out the correction factor for LMTD.

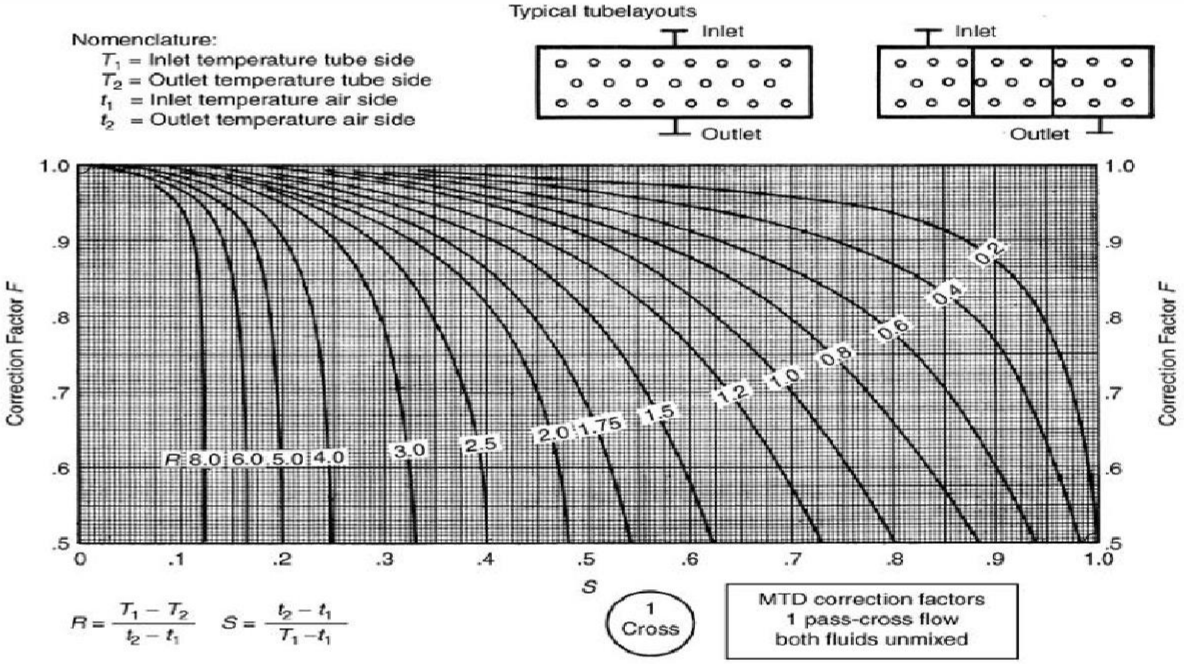


Figure 6.2 Correction Factor for Economizer 1

Correction factor = 0.96

Corrected LMTD = ΔT_m = 0.96 x 113.16 = 108.63 C

- **Total Heat Transfer Area:**

Q = 1424.69 kW, U = 699.41 W/m^2K

$$A_{ireq} = {}^{Q}/_{U \times \Delta T_m}$$

$$= 40.89\ m^2$$

- **Heat Transfer Area per pass:**

Area = A_{ireq} / N_p

Area = 6.82 m^2

- **Total Number of Tubes:**

$\text{Tubes} = N_p \text{ x } N_t$

$\text{Tubes} = 186$

6.1.1.4 Pressure Drop Calculations

6.1.1.4.1 Fin Side:

- **Net Free Volume:**

$V_{fv} = \text{⍰⍰⍰}' - (N_t \times \text{⍰}/4 \text{ x } (TOD^2) \text{ x } L) - (N_p \text{ x } t_f \text{ x } N_f \text{ x } \text{⍰} \times (FOD^2 - TOD^2))$

$V_{fv} = 0.18 \text{ m}^3$

- **Volumetric Equivalent Diameter:**

$D_{ev} = 4 \text{ x } (V_{fv} / ((A_f \text{ x } L) + (A_b \text{x } L)) \text{ x } (N_p)$

$D_{ev} = 0.01 \text{ m}$

- **Reynold Number for Pressure Drop:**

$Re = (D_{ev} * Gs) / \mu$

$Re = 1844.09$

- **Fin Side Fan Friction Factor:**

$J_{fa} = 1.08558 \text{ x } Re^{-0.128025}$

$J_{fa} = 0.41$

- **Effective Path Length for Pressure Drop:**

$L_p = \text{⍰}' \text{ x } N_p$

$L_p = 0.83 \text{ m}^3$

- **Pressure Drop:**

$$\Delta P_s = (J_{fa} \times Gs^2 \times L_p / D_{ev} \times \rho_{wh}) \times (D_{ev} / S_t)^{0.4} \times (S_l / S_t)^{0.6}$$

$$\Delta P_s = 22240.52 \ N/m^2 = 3.23 \ psi$$

6.1.1.4.2 Tube Side:

- **Tube Side Friction Factor:**

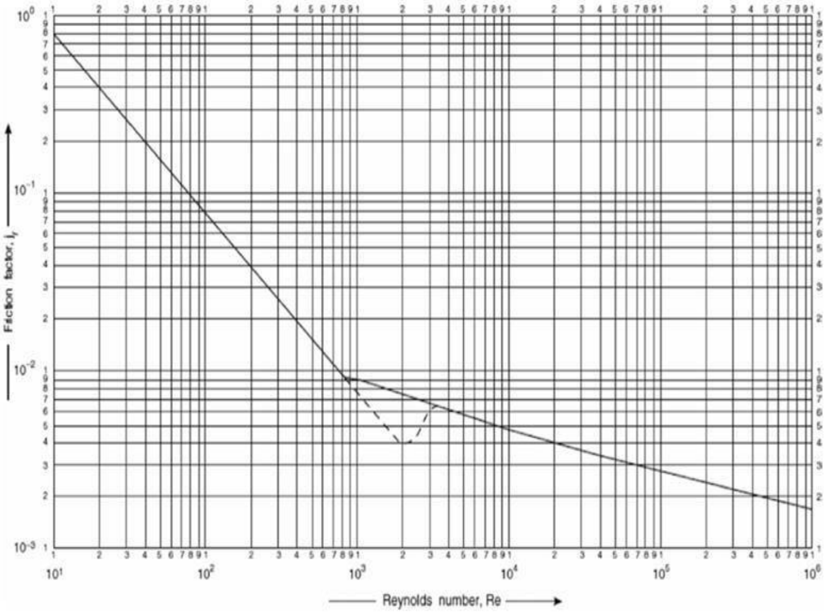


Fig. A4. Friction Factor for Tube Side [4].

Figure 6.3 friction factor for tube side of Economizer 1

From the above graph, $J_f = 0.0042$

- **Pressure Drop:**

$$\Delta P_t = N_p \times (8 \times J_f \times (L / TID) + 2.5) \times (\rho_w \times \mu_t^2/2)$$

$$\Delta P_t = 4227.32 \ Pa = 0.61 \ psi$$

6.1.2 Evaporator:

Assumptions (Schedule No. 40)

Tube Outer Diameter (TOD) = 17.75 mm

Tube Inner Diameter (TID) = 14.84 mm

Thickness of Tube = 2.31 mm

Fin Outer Diameter (FOD) = 40.3 mm

Thickness of Fin (t_f) = 0.12 mm

Number of fins per unit length (N_f) = 562

Effective Length of tube (L) = 1.72 m

Length of heat exchanger tube sheet (W) = 3.21 m

Distance b/w fin ends = 0.857 cm

Number of Passes (Np) = 6

6.1.2.1 Fin Side Calculations

- **Fin Area / unit tube length:**

$$A_f = (\pi/4)\ (FOD^2 - TOD^2) \times 2 \times N_f$$

$$A_f = 1.17\ m^2/m \text{ tube length}$$

- **Bare Tube Area:**

$$A_b = (\pi \times TOD) - \pi \times TOD \times t_f \times N_f$$

$$A_b = 0.05\ m^2/m \text{ tube length}$$

- **Projected Perimeter:**

$$P_e = 2 \times (FOD-TOD) \times N_f + 2 \times (1 - t_f \times N_f)$$

$$P_e = 27.89\ m/m \text{ tube length}$$

- **Equivalent Diameter:**

$$D_e = 2 \times (A_f + A_b) / (\pi \times P_e)$$

$$D_e = 0.03$$

- **Fin Side Side Flow Area:**

$a_s = (LW) – (N_p x\ TOD\ x\ L) – (N_p\ x\ t_f\ x\ n_f\ x\ L\ x\ (FOD – TOD)\ )$

$a_s = 4.41\ m^2$

- **Fin Side Mass Velocity:**

$m^{\cdot} = 25.4$ kg/s (given)

$G_s = m^{\cdot} / N_f$

$G_s = 5.76\ kg / s\ m^2$

- **Fin Side Reynolds Number:**

$\mu = 3.31x\ 10^{-5}$ (literature)

$R_e = D_e\ x\ (G_s / \mu)$

$R_e = 4863.74$

- **Fin Side Prandtl Number:**

$C_p = 1312$ J/kg.K , k = 0.0396 W/m.K (literature)

$P_r = (\mu\ C_p) / k$

$P_r = 1.10$

- **Number of tubes in a bundle:**

$N_t = (L / TOD) + 2 +$ (Distance b/w fin ends)

$N_t = 38$

- **Factor of heat transfer coefficient:**

$J_{ha} = 0.0852072\ x\ Re^{0.7324}$

$J_{ha} = 42.74$

- **Clean heat transfer coefficient:**

$h_f = J_{ha}\ (k / D_e\ ) x\ P_r^{1/3}$

$h_f = 62.44\ W / m^2K$

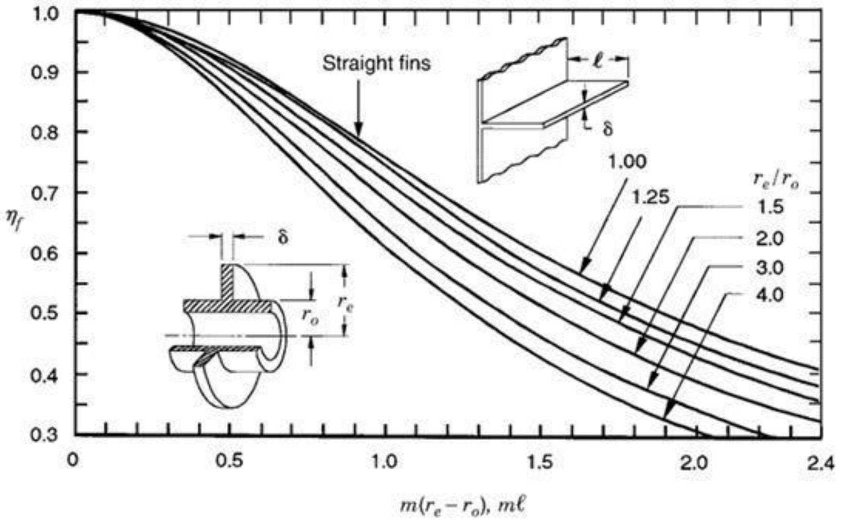


Figure 6.4 Fin Efficiency of Evaporator

- **Fin Efficiency:**

r_e = radius of finned tube = 40.30 / 2 = 201.15 mm

r_b = radius of bare tube = 17.75 / 2 = 8.58mm

k_f = thermal conductivity of aluminum = 237 W/m.K (literature)

$\eta = \tanh m \times (r_e - r_b) / m \times (r_e - r_b)$

$m = (2 \times h_f / k_f \times t_f)^{1/2}$

$\eta = 0.84$

- **Dirty fin side heat transfer coefficient:**

$h_{ft} = (\eta \times A_b + A_f) \times (h_f / \pi) \times TID$

$h_f = 1390 \text{ W} / \text{m}^2\text{K}$

6.1.2.2 Tube Side Calculations

- **Inner Tube Area:**

$a_t = N_t \times (\pi/4) (TID^2)$

$a_t = 0.007 \text{ m}^2$

- **Tube Mass Velocity:**

$\dot{m}_w = 7.408$ kg/s (given)

$G_t = \dot{m}_w \times a_t$

$G_t = 1138.32$ kg / s m^2

- **Tube Velocity:**

$\rho = 934.8$ kg/m^3 (literature)

$u_t = G_t / \rho$

$u_t = 1.22$ m / s

- **Tube Side Reynolds Number:**

$\mu_w = 2.18 \times 10^{-4}$ kg/m.s (literature)

$R_{et} = (TID \times G_t) / \mu_w$

$R_{et} = 77560.53$

- **Tube Side Prandtl Number:**

$C_{pw} = 4260$ J/kg.K , $k_w = 0.0687$ W/m.K (literature)

$P_{rt} = (\mu_w \times C_{pw}) / k_w$

$P_{rt} = 13.51$

- **Internal Heat Transfer Coefficient:**

$h_i = (0.023 \times R_{et}^{0.8} \times P_{rt}^{0.33} \times k_w) / TID$

$h_i = 2051.31$ W / m^2 x K

- **Fouling Factor Coefficient:**

$h_{id} = 4487 \text{ W / m}^2 \times \text{K}$

- **Overall Heat Transfer Coefficient:**

$1/U = (1/h_{ft}) + (1/h_i) + (1/h_{id})$

$U = 700 \text{ W/m}^2 \text{ K}$

6.1.2.3 Area Calculations and Total Tubes

First, we will calculate the Logarithmic Mean Temperature Difference (LMTD):

Inlet Hot Stream Temperature = 238.9 C

Outlet Hot Stream Temperature = 207.5 C

Inlet Cold Stream Temperature = 130 C

Outlet Cold Stream Temperature = 190 C

$$\boxed{\Delta T_{lm} = \frac{(T_{Hin} - T_{Cout}) - (T_{Hout} - T_{Cin})}{\ln \dfrac{(T_{Hin} - T_{Cout})}{(T_{Hout} - T_{Cin})}}}$$

$\Delta T_{lm} = 62.11 \text{ C}$

By using the graph below we find out the correction factor for LMTD.

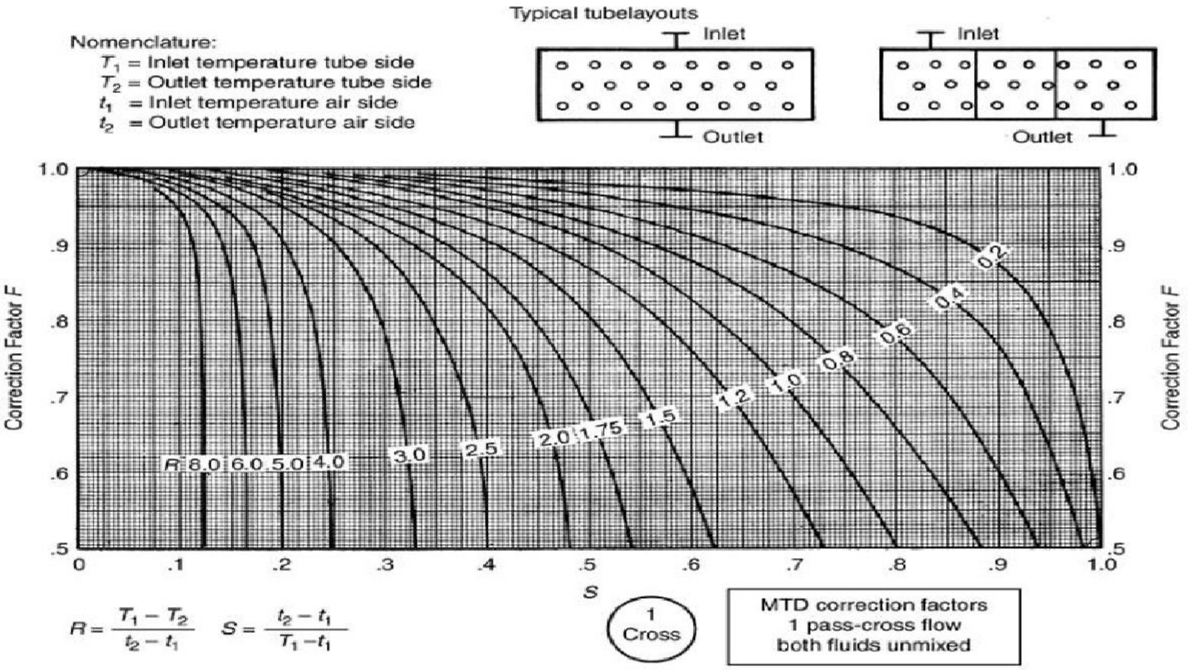


Figure 6.5 Correction Factor for Evaporator

Correction factor = 0.92

Corrected LMTD = $\Delta T_m = 0.92 \times 62.11 = 57.14$ C

- **Total Heat Transfer Area:**

$Q = 2047.51$ kW, $U = 700$ W/m^{2}K

$$A_{ireq} = Q / U \times \Delta T_m$$

$$= 51.24 \text{ m}^2$$

- **Heat Transfer Area per pass:**

$$\text{Area} = A_{ireq} / N_p$$

$$\text{Area} = 8.54 \text{ m}^2$$

- **Total Number of Tubes:**

$$\text{Tubes} = N_p \times N_t$$

Tubes = 228

6.1.2.4 Pressure Drop Calculations

6.1.2.4.1 Fin Side:

- **Net Free Volume:**

$V_{fv} = \square\square\square' - (N_t \times \square/4 \text{ x } (TOD^2) \text{ x } L) - (N_p \text{ x } t_f \text{ x } N_f \text{ x } \square \times (FOD^2 - TOD^2))$

$V_{fv} = 0.19 \ m^3$

- **Volumetric Equivalent Diameter:**

$D_{ev} = 4 \text{ x } (V_{fv} / ((A_f \text{ x } L) + (A_b \text{x } L)) \text{ x } (N_p)$

$D_{ev} = 0.01 \text{ m}$

- **Reynold Number for Pressure Drop:**

$Re = (D_{ev} * Gs) / \mu$

$Re = 1707.85$

- **Fin Side Fan Friction Factor:**

$J_{fa} = 1.08558 \text{ x } Re^{-0.128025}$

$J_{fa} = 0.42$

- **Effective Path Length for Pressure Drop:**

$L_p = \square' \text{ x } N_p$

$L_p = 0.83 \ m^3$

- **Pressure Drop:**

$\Delta P_s = (J_{fa} \text{ x } Gs^2 \text{ x } L_p / D_{ev} \text{ x } \rho_{wh}) \text{ x } (D_{ev} / S_t)^{0.4} \text{ x } (S_l / S_t)^{0.6}$

$\Delta P_s = 18683.15 \text{ N/m}^2 = 2.71 \text{ psi}$

6.1.2.4.2 Tube Side:

- **Tube Side Friction Factor:**

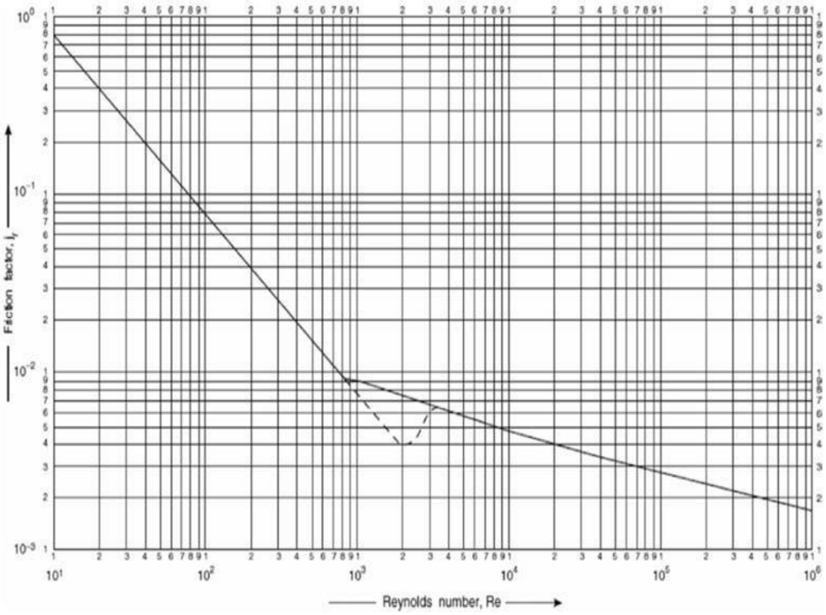


Fig. A4. Friction Factor for Tube Side [4].

Figure 6.6 Friction Factor for Evaporator

From the above graph, $J_f = 0.0025$

- **Pressure Drop:**

$\Delta P_t = N_p \text{ x } (8 \text{ x } J_f \text{ x } (L / TID) + 2.5) \text{ x } (\rho_w \text{ x } \mu_t^2/2)$

$\Delta P_t = 17722.19 \text{ Pa} = 1.94 \text{ psi}$

Similar Calculations are done for other components of the Heat Recovery Steam Generator. All major ones are provided in the table below.

Table 6.1 Required Calculation of HRSG

		Eco 1	Eco 2	Evap 1	Reheater	Evap 2	Spheater 1	Spheater 2
LMTD (c)		108.63	82.22	57.14	26.74	65.20	143.33	67.75
Heat transfer area (m^2)		40.89	39.30	51.24	32.57	28.68	37.38	38.81
No. of tubes		186	206	225	265	225	166	225
Pressure Drop (psi)	**Fin Side**	3.23	3.05	2.71	2.3	5.55	4.56	5.16
	Tube Side	0.61	0.93	1.94	1.26	2.41	0.20	3.6

6.2 Steam Drum

The pressure entering the steam drum is 56.08 kg/cm^2.

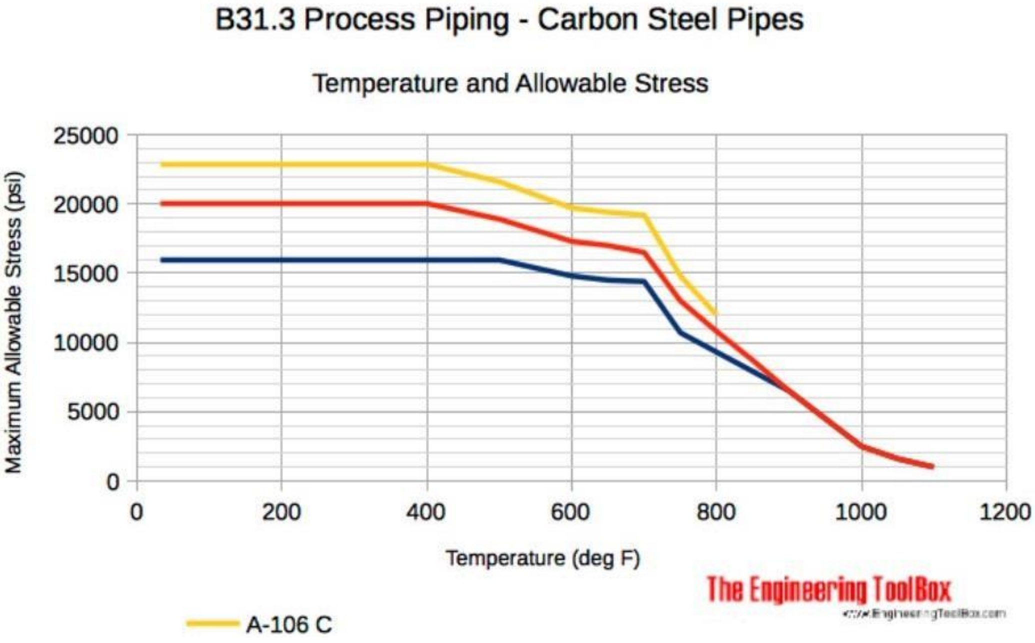


Figure 6.7 Maximum allowable stress for steam drum

By using the graph above we found out the maximum allowable stress at inlet temperature at 520 F to be 1406 kg/cm^2.

Data:

Thickness (T) = 30mm (Assumption)

Internal Diameter (D) = 1200 mm (Assumption)

Pressure (P) = 56.08 kg/cm^2

Maximum Allowable Stress (f) = 1406 kg/cm^2

Calculations:

- **Allowable Working Pressure:**

$$WP = {}^{2 \text{ x f x } (T - 0.762)}/_{(D + T - 0.762)}$$

$$= 66.90 \text{ kg/cm}^2$$

This shows that our pressure is acceptable as it is lesser than the allowable pressure steam drum can work on.

- **Minimum Required Thickness:**

$$WP = {}^{(P \text{ x } D)}/_{(2 \text{ x f})} + 0.762$$

$$= 24.7 \text{ mm}$$

This shows that the thickness we assumed is greater than the minimum required thickness, so it is acceptable.

6.3 Turbines

6.3.1 Gas Turbine

From the ideal gas equation, the volumetric flowrates of the turbines are calculated.

$$\mathbf{PV = nRT}$$

- **Inlet:**

Pressure (P) = 3×10^6 Pa

Temperature (T) = 1308 K

Molar Flow (n) = 7525 mol/hr

Gas Constant (R) = 8.314 J/mol.K

Now,

Volumetric Flow Rate (V) $$= \frac{\mathbf{7525\ x\ 8.314\ x\ 1308}}{\mathbf{3\ x\ 10^6}}$$

$$\mathbf{= 27.28\ m^3/hr}$$

- **Outlet:**

Pressure (P) = 1.3×10^5 Pa

Temperature (T) = 733.16 K

Molar Flow (n) = 7525 mol/hr

Gas Constant (R) = 8.314 J/mol.K

Now,

Volumetric Flow Rate (V) $$= \frac{\mathbf{7525\ x\ 8.314\ x\ 733.16}}{\mathbf{1.3\ x\ 10^5}}$$

$$\mathbf{= 352.84\ m^3/hr}$$

This shows that the inlet volumetric flow rate is less than the outlet one. This is because the turbine decreases the pressure and produces power while increasing the volume by expansion.

Now calculating the efficiency of the turbine,

$$\eta_t = \frac{1-(\frac{p2}{p1})^{\eta p(\gamma-1)}/_{\gamma}}{1-(\frac{p2}{p1})^{(\gamma-1)}/_{\gamma}}$$

Heat Capacity Ratio = $\gamma = 1.319$

Polytropic Efficiency = $\eta_p = 66.7$ %

Inlet Pressure = p_1 = 30 bar

Outlet Pressure = p_2 = 1.363 bar

$$\text{Pressure Ratios} = \frac{p_2}{p_1} = 0.045$$

Putting values in the equation we get the efficiency,

Turbine Efficiency = η_t = 0.746

6.3.2 Steam Turbines

As in the gas turbines, ideal gas equation will also be used here to calculate volumetric calculation.

6.3.2.1 High Pressure (HP)

- **Inlet:**

  Pressure (P) = 5.5×10^6 Pa
  Temperature (T) = 753 K
  Molar Flow (n) = 1480 mol/hr
  Gas Constant (R) = 8.314 J/mol.K
  Now,

  Volumetric Flow Rate (V) $= \dfrac{1480 \times 8.314 \times 753}{5.5 \times 10^6}$

  = 1.68 m^3/hr

- **Outlet:**

  Pressure (P) = 3.5×10^6 Pa
  Temperature (T) = 693.9 K
  Molar Flow (n) = 1480 mol/hr
  Gas Constant (R) = 8.314 J/mol.K

Now,

Volumetric Flow Rate (V) $= \dfrac{\mathbf{1480 \, x \, 8.314 \, x \, 693.9}}{\mathbf{3.5 \, x \, 10^5}}$

$= 2.44$ m^3/hr

This shows that the inlet volumetric flow rate is less than the outlet one. This is because the turbine decreases the pressure and produces power while increasing the volume by expansion.

Now calculating the efficiency of the turbine,

$$\eta_t = \frac{1-\left(\frac{p2}{p1}\right)^{\eta p(\gamma-1)}/\gamma}{1-\left(\frac{p2}{p1}\right)^{(\gamma-1)}/\gamma}$$

Heat Capacity Ratio = $\gamma = 1.36$

Polytropic Efficiency = $\eta_p = 75\ \%$

Inlet Pressure = $p_1 = 55$ bar

Outlet Pressure = $p_2 = 35$ bar

Pressure Ratios = $\frac{p_2}{p_1} = 0.636$

Putting values in the equation we get the efficiency,

Turbine Efficiency = η_t = 0.761

Similar calculations are done for other steam turbines. Values are displayed below.

Table 6.2 Required calculation of Steam Turbines

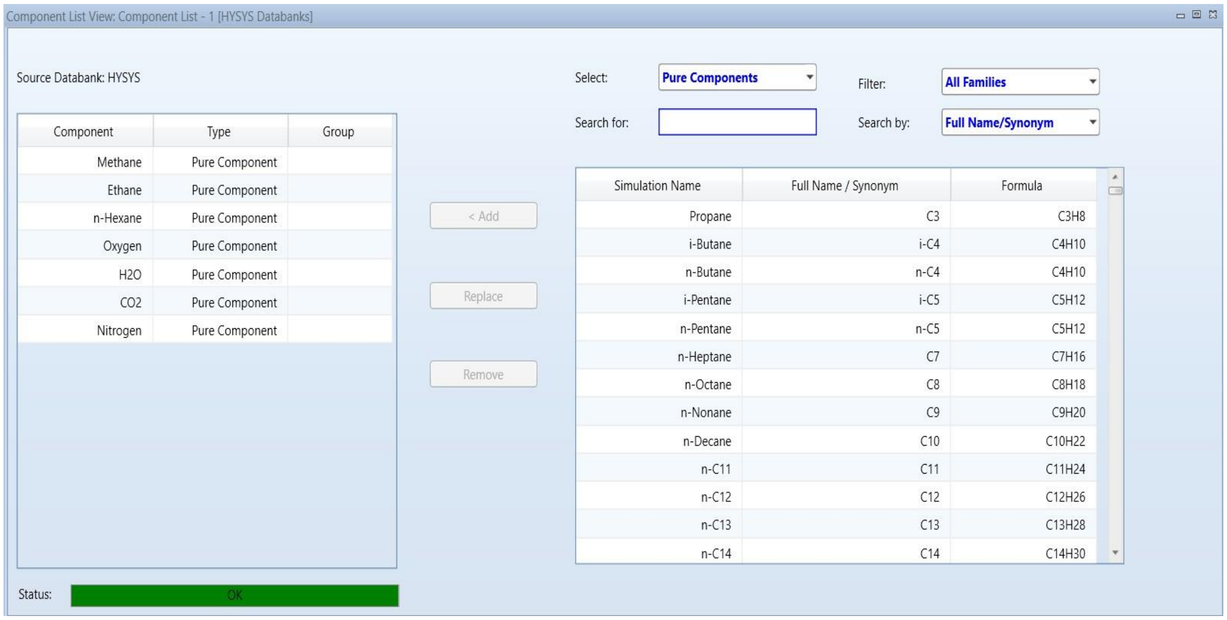
		IP 1	**IP 2**	**LP**
V (m^3/hr)	**IN**	2.44	3.57	5.61
	OUT	3.43	5.61	8.68
Efficiency		0.751	0.754	0.753

CHAPTER 7

SIMULATION

7.1 Components

The simulation of whole combined cycle powerplant was made on Aspen Hysys. The required components were selected from HYSYS properties database are listed here in figure:



Source Databank: HYSYS

Select: Pure Components

Filter: All Families

Search for:

Search by: Full Name/Synonym

Component	Type	Group
Methane	Pure Component	
Ethane	Pure Component	
n-Hexane	Pure Component	
Oxygen	Pure Component	
H2O	Pure Component	
CO2	Pure Component	
Nitrogen	Pure Component	

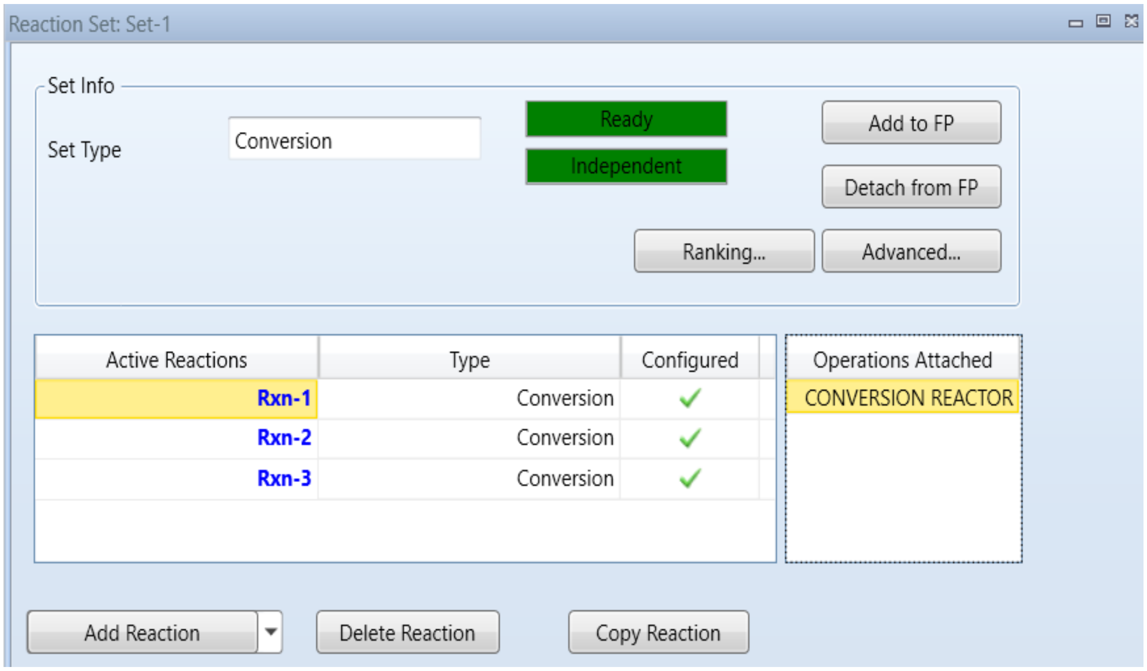
Simulation Name	Full Name / Synonym	Formula
Propane	C3	C3H8
i-Butane	i-C4	C4H10
n-Butane	n-C4	C4H10
i-Pentane	i-C5	C5H12
n-Pentane	n-C5	C5H12
n-Heptane	C7	C7H16
n-Octane	C8	C8H18
n-Nonane	C9	C9H20
n-Decane	C10	C10H22
n-C11	C11	C11H24
n-C12	C12	C12H26
n-C13	C13	C13H28
n-C14	C14	C14H30

Status: OK

Figure 7.1 Component List

7.2 Reactions:

Three combustion reactions are added. Combustible components are methane, hexane, ethane.



Reaction Set: Set-1

Set Info

Set Type: Conversion

Ready

Independent

Active Reactions	Type	Configured
Rxn-1	Conversion	✓
Rxn-2	Conversion	✓
Rxn-3	Conversion	✓

Operations Attached
CONVERSION REACTOR

Figure 7.2 Reaction set

7.3 Simulation Model

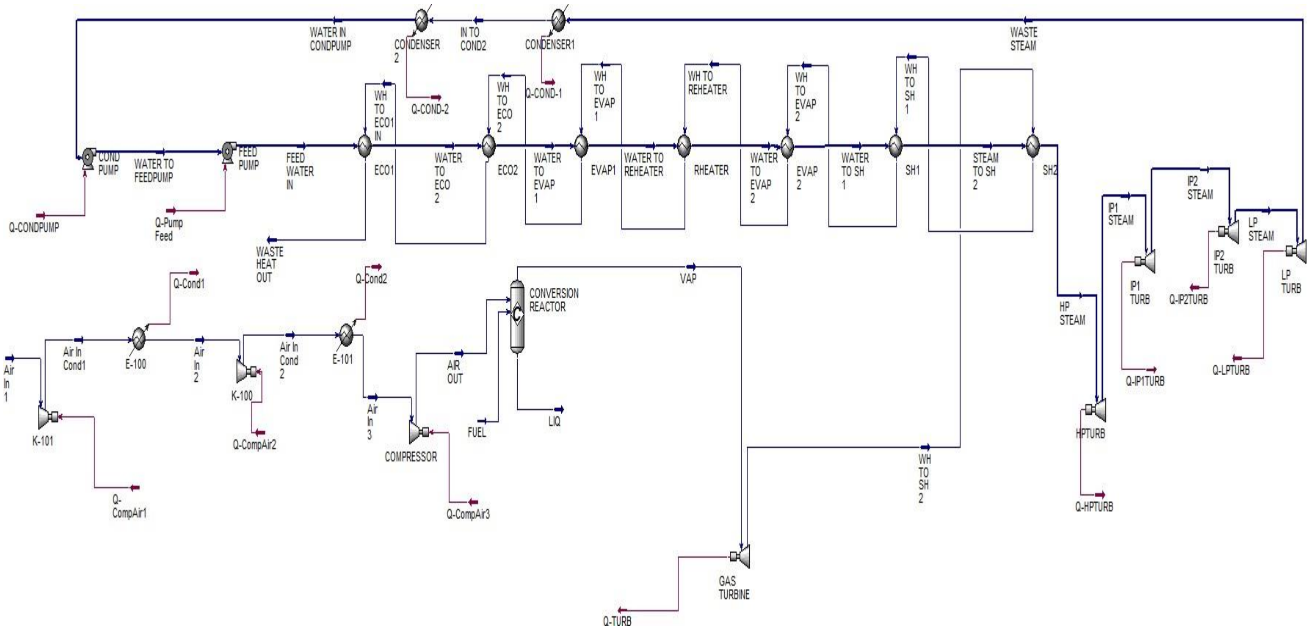
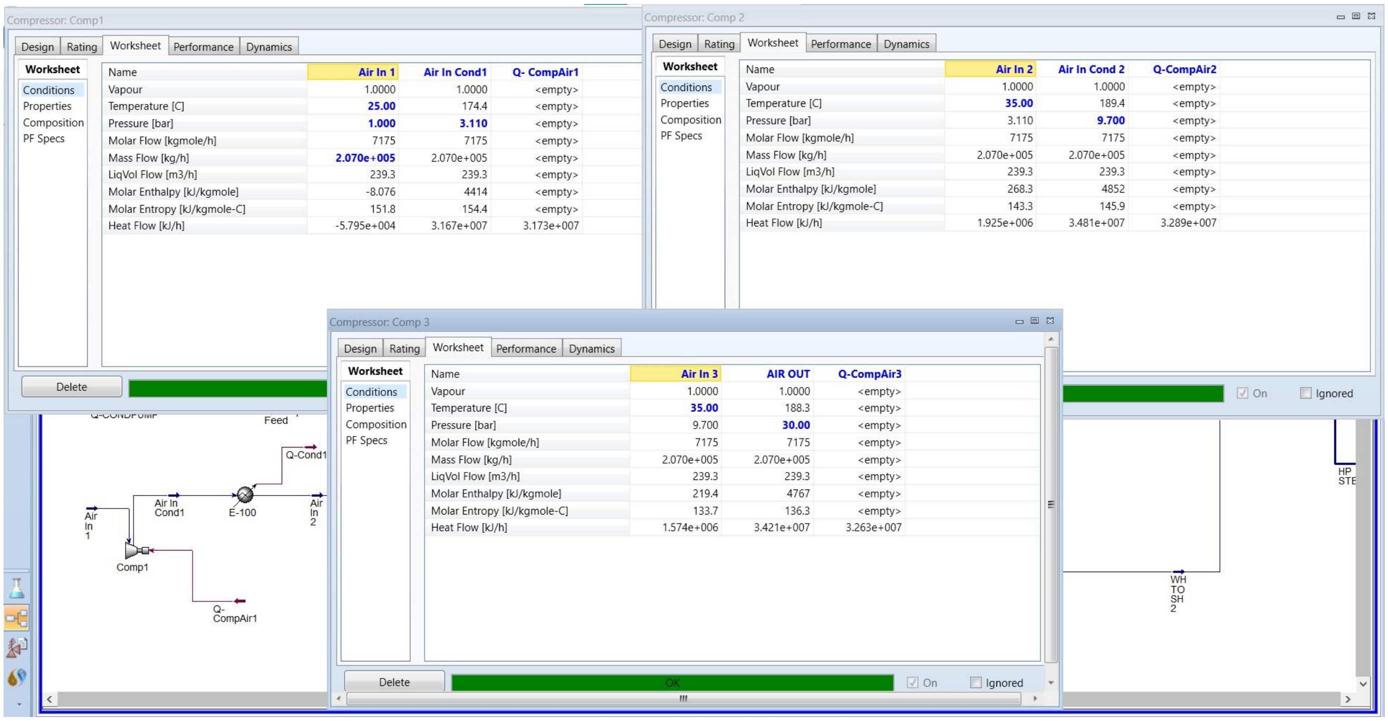


Figure 7.3 Overall Simulation Process

7.4 Compressor:



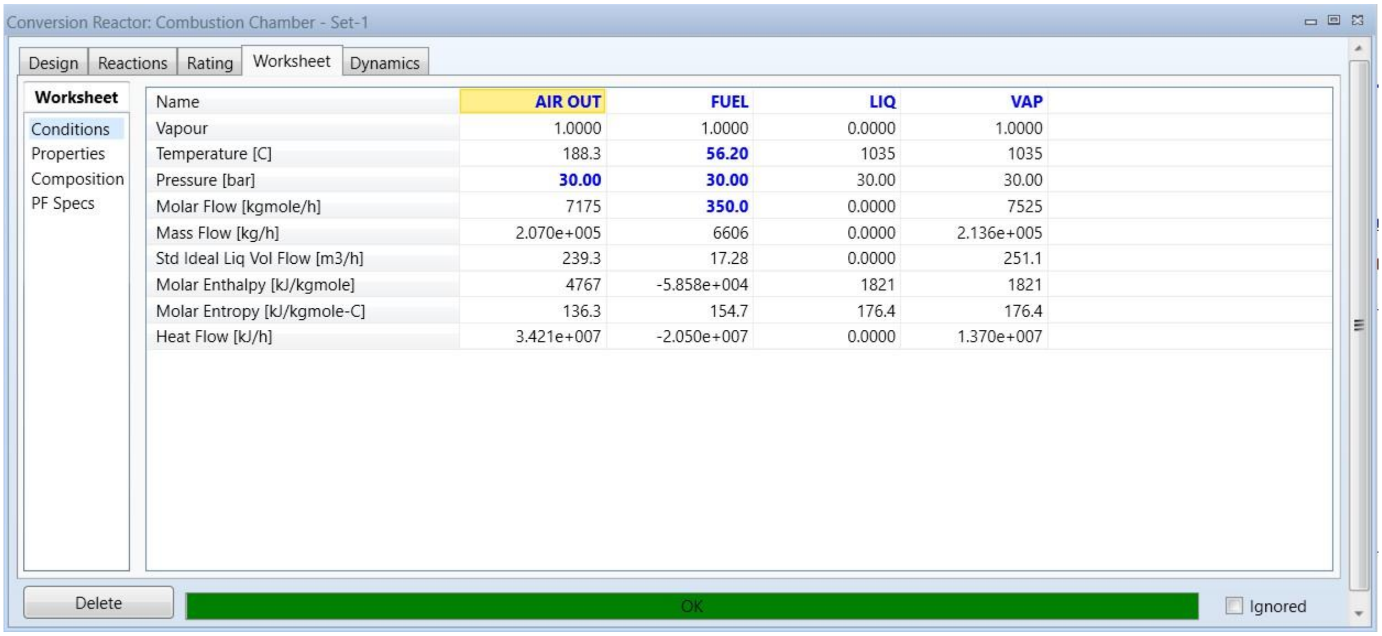
Name	Air In 1	Air In Cond1	Q- CompAir1
Vapour	1.0000	1.0000	<empty>
Temperature [C]	25.00	174.4	<empty>
Pressure [bar]	1.000	3.110	<empty>
Molar Flow [kgmole/h]	7175	7175	<empty>
Mass Flow [kg/h]	2.070e+005	2.070e+005	<empty>
LiqVol Flow [m3/h]	239.3	239.3	<empty>
Molar Enthalpy [kJ/kgmole]	-8.076	4414	<empty>
Molar Entropy [kJ/kgmole-C]	151.8	154.4	<empty>
Heat Flow [kJ/h]	-5.795e+004	3.167e+007	3.173e+007

Name	Air In 2	Air In Cond 2	Q-CompAir2
Vapour	1.0000	1.0000	<empty>
Temperature [C]	35.00	189.4	<empty>
Pressure [bar]	3.110	9.700	<empty>
Molar Flow [kgmole/h]	7175	7175	<empty>
Mass Flow [kg/h]	2.070e+005	2.070e+005	<empty>
LiqVol Flow [m3/h]	239.3	239.3	<empty>
Molar Enthalpy [kJ/kgmole]	268.3	4852	<empty>
Molar Entropy [kJ/kgmole-C]	143.3	145.9	<empty>
Heat Flow [kJ/h]	1.925e+006	3.481e+007	3.289e+007

Name	Air In 3	AIR OUT	Q-CompAir3
Vapour	1.0000	1.0000	<empty>
Temperature [C]	35.00	188.3	<empty>
Pressure [bar]	9.700	30.00	<empty>
Molar Flow [kgmole/h]	7175	7175	<empty>
Mass Flow [kg/h]	2.070e+005	2.070e+005	<empty>
LiqVol Flow [m3/h]	239.3	239.3	<empty>
Molar Enthalpy [kJ/kgmole]	219.4	4767	<empty>
Molar Entropy [kJ/kgmole-C]	133.7	136.3	<empty>
Heat Flow [kJ/h]	1.574e+006	3.421e+007	3.263e+007

Figure 7.4 Multistage Compressor

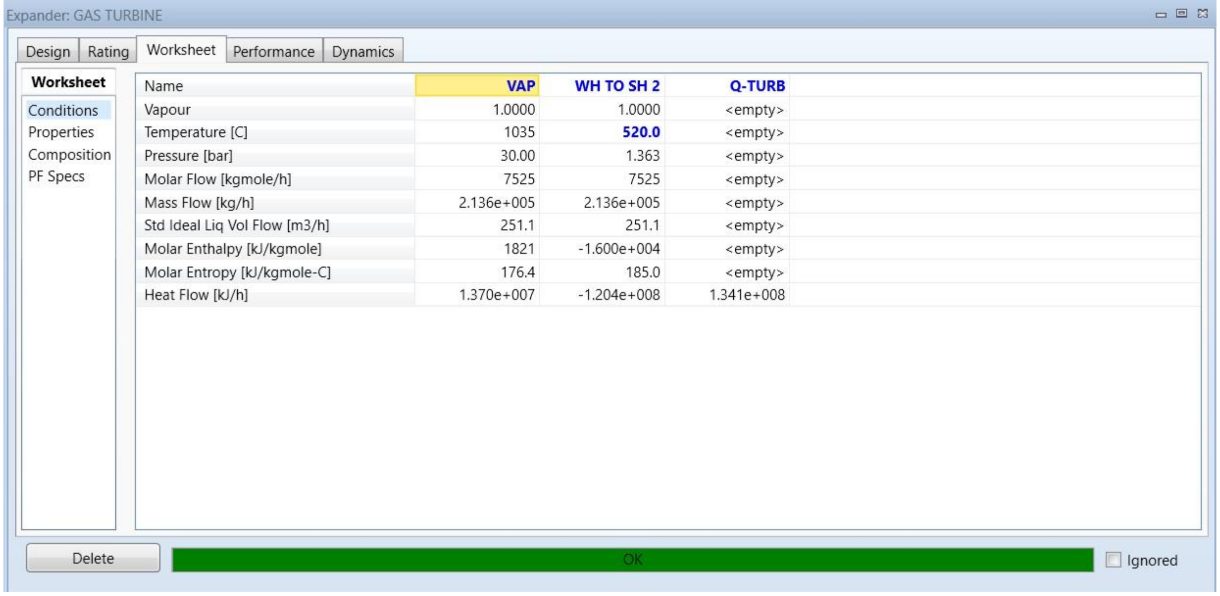
7.5 Combustion Chamber:



Name	AIR OUT	FUEL	LIQ	VAP
Vapour	1.0000	1.0000	0.0000	1.0000
Temperature [C]	188.3	56.20	1035	1035
Pressure [bar]	30.00	30.00	30.00	30.00
Molar Flow [kgmole/h]	7175	350.0	0.0000	7525
Mass Flow [kg/h]	2.070e+005	6606	0.0000	2.136e+005
Std Ideal Liq Vol Flow [m3/h]	239.3	17.28	0.0000	251.1
Molar Enthalpy [kJ/kgmole]	4767	-5.858e+004	1821	1821
Molar Entropy [kJ/kgmole-C]	136.3	154.7	176.4	176.4
Heat Flow [kJ/h]	3.421e+007	-2.050e+007	0.0000	1.370e+007

Figure 7.5 Combustion Chamber

7.6 Gas Turbine:

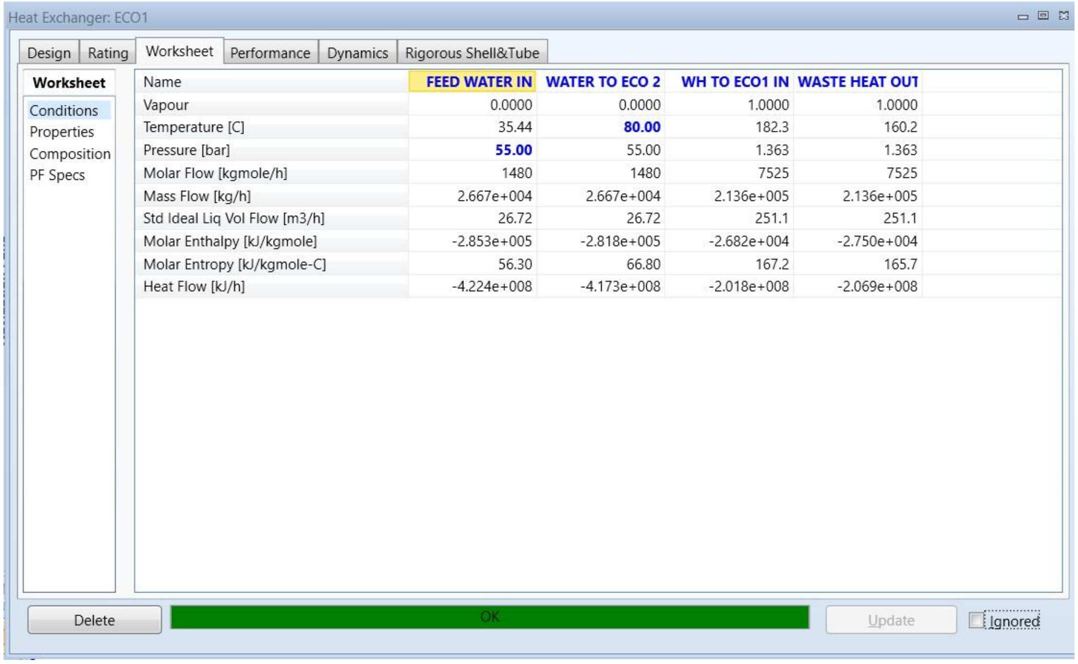


Name	VAP	WH TO SH 2	Q-TURB
Vapour	1.0000	1.0000	<empty>
Temperature [C]	1035	520.0	<empty>
Pressure [bar]	30.00	1.363	<empty>
Molar Flow [kgmole/h]	7525	7525	<empty>
Mass Flow [kg/h]	2.136e+005	2.136e+005	<empty>
Std Ideal Liq Vol Flow [m3/h]	251.1	251.1	<empty>
Molar Enthalpy [kJ/kgmole]	1821	-1.600e+004	<empty>
Molar Entropy [kJ/kgmole-C]	176.4	185.0	<empty>
Heat Flow [kJ/h]	1.370e+007	-1.204e+008	1.341e+008

Figure 7.6 Gas Turbine

7.7 Heat Recovery Steam Generator:

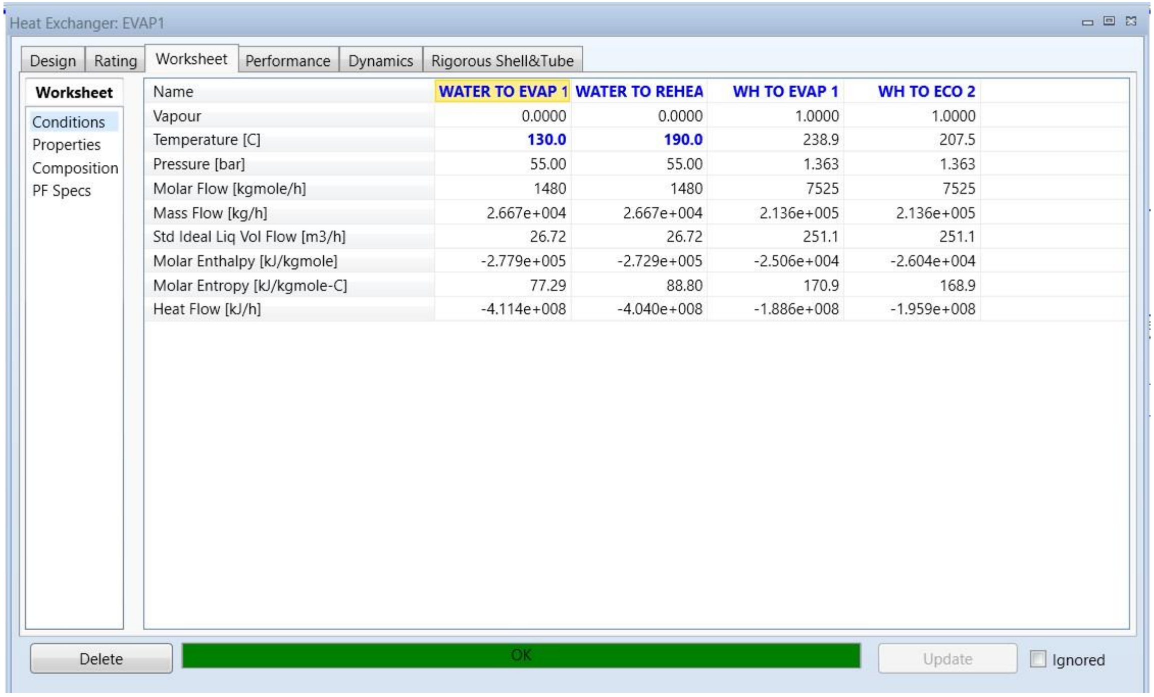
7.7.1 Economizer:



Name	FEED WATER IN	WATER TO ECO 2	WH TO ECO1 IN	WASTE HEAT OUT
Vapour	0.0000	0.0000	1.0000	1.0000
Temperature [C]	35.44	80.00	182.3	160.2
Pressure [bar]	55.00	55.00	1.363	1.363
Molar Flow [kgmole/h]	1480	1480	7525	7525
Mass Flow [kg/h]	2.667e+004	2.667e+004	2.136e+005	2.136e+005
Std Ideal Liq Vol Flow [m3/h]	26.72	26.72	251.1	251.1
Molar Enthalpy [kJ/kgmole]	-2.853e+005	-2.818e+005	-2.682e+004	-2.750e+004
Molar Entropy [kJ/kgmole-C]	56.30	66.80	167.2	165.7
Heat Flow [kJ/h]	-4.224e+008	-4.173e+008	-2.018e+008	-2.069e+008

Figure 7.7 Economizer

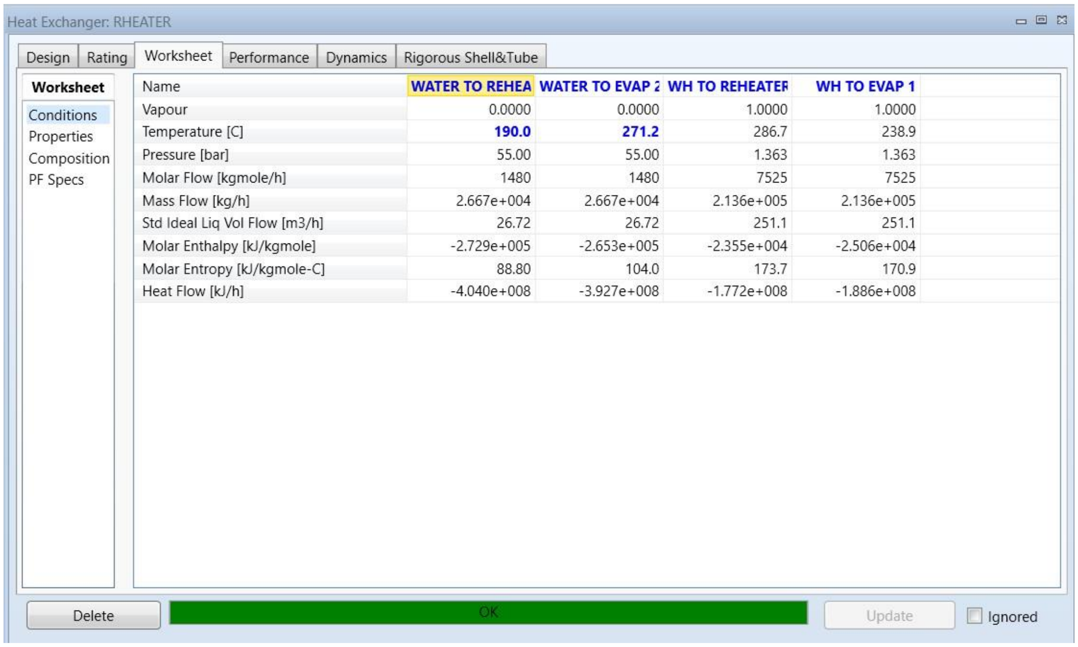
7.7.2 Evaporator:



Name	WATER TO EVAP 1	WATER TO REHEA	WH TO EVAP 1	WH TO ECO 2
Vapour	0.0000	0.0000	1.0000	1.0000
Temperature [C]	**130.0**	**190.0**	238.9	207.5
Pressure [bar]	55.00	55.00	1.363	1.363
Molar Flow [kgmole/h]	1480	1480	7525	7525
Mass Flow [kg/h]	2.667e+004	2.667e+004	2.136e+005	2.136e+005
Std Ideal Liq Vol Flow [m3/h]	26.72	26.72	251.1	251.1
Molar Enthalpy [kJ/kgmole]	-2.779e+005	-2.729e+005	-2.506e+004	-2.604e+004
Molar Entropy [kJ/kgmole-C]	77.29	88.80	170.9	168.9
Heat Flow [kJ/h]	-4.114e+008	-4.040e+008	-1.886e+008	-1.959e+008

Figure 7.8 Evaporator

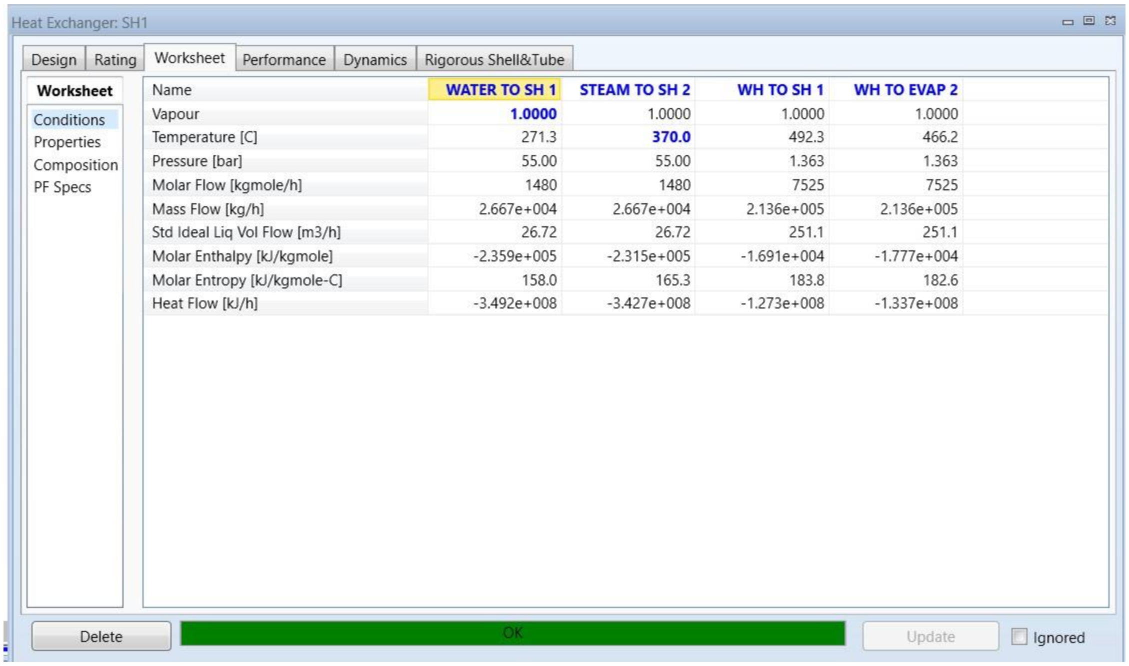
7.7.3 Reheater:



Name	WATER TO REHEA	WATER TO EVAP	WH TO REHEATE	WH TO EVAP 1
Vapour	0.0000	0.0000	1.0000	1.0000
Temperature [C]	**190.0**	**271.2**	286.7	238.9
Pressure [bar]	55.00	55.00	1.363	1.363
Molar Flow [kgmole/h]	1480	1480	7525	7525
Mass Flow [kg/h]	2.667e+004	2.667e+004	2.136e+005	2.136e+005
Std Ideal Liq Vol Flow [m3/h]	26.72	26.72	251.1	251.1
Molar Enthalpy [kJ/kgmole]	-2.729e+005	-2.653e+005	-2.355e+004	-2.506e+004
Molar Entropy [kJ/kgmole-C]	88.80	104.0	173.7	170.9
Heat Flow [kJ/h]	-4.040e+008	-3.927e+008	-1.772e+008	-1.886e+008

Figure 7.9 Reheater

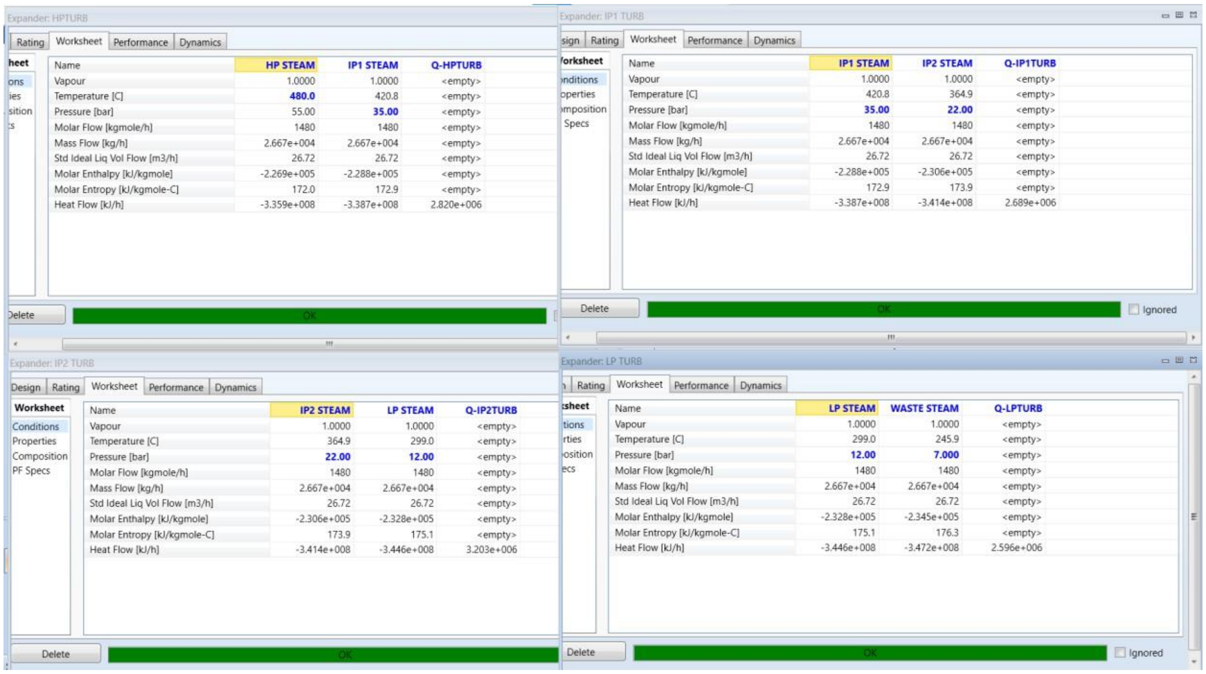
7.7.4 Superheater:



Name	WATER TO SH 1	STEAM TO SH 2	WH TO SH 1	WH TO EVAP 2
Vapour	1.0000	1.0000	1.0000	1.0000
Temperature [C]	271.3	370.0	492.3	466.2
Pressure [bar]	55.00	55.00	1.363	1.363
Molar Flow [kgmole/h]	1480	1480	7525	7525
Mass Flow [kg/h]	2.667e+004	2.667e+004	2.136e+005	2.136e+005
Std Ideal Liq Vol Flow [m3/h]	26.72	26.72	251.1	251.1
Molar Enthalpy [kJ/kgmole]	-2.359e+005	-2.315e+005	-1.691e+004	-1.777e+004
Molar Entropy [kJ/kgmole-C]	158.0	165.3	183.8	182.6
Heat Flow [kJ/h]	-3.492e+008	-3.427e+008	-1.273e+008	-1.337e+008

Figure 7.10 Superheater

7.7.5 Steam Turbines:



Name	HP STEAM	IP1 STEAM	Q-HPTURB
Vapour	1.0000	1.0000	<empty>
Temperature [C]	480.0	420.8	<empty>
Pressure [bar]	55.00	35.00	<empty>
Molar Flow [kgmole/h]	1480	1480	<empty>
Mass Flow [kg/h]	2.667e+004	2.667e+004	<empty>
Std Ideal Liq Vol Flow [m3/h]	26.72	26.72	<empty>
Molar Enthalpy [kJ/kgmole]	-2.269e+005	-2.288e+005	<empty>
Molar Entropy [kJ/kgmole-C]	172.0	172.9	<empty>
Heat Flow [kJ/h]	-3.359e+008	-3.387e+008	2.820e+006

Name	IP1 STEAM	IP2 STEAM	Q-IP1TURB
Vapour	1.0000	1.0000	<empty>
Temperature [C]	420.8	364.9	<empty>
Pressure [bar]	35.00	22.00	<empty>
Molar Flow [kgmole/h]	1480	1480	<empty>
Mass Flow [kg/h]	2.667e+004	2.667e+004	<empty>
Std Ideal Liq Vol Flow [m3/h]	26.72	26.72	<empty>
Molar Enthalpy [kJ/kgmole]	-2.288e+005	-2.306e+005	<empty>
Molar Entropy [kJ/kgmole-C]	172.9	173.9	<empty>
Heat Flow [kJ/h]	-3.387e+008	-3.414e+008	2.689e+006

Name	IP2 STEAM	LP STEAM	Q-IP2TURB
Vapour	1.0000	1.0000	<empty>
Temperature [C]	364.9	299.0	<empty>
Pressure [bar]	22.00	12.00	<empty>
Molar Flow [kgmole/h]	1480	1480	<empty>
Mass Flow [kg/h]	2.667e+004	2.667e+004	<empty>
Std Ideal Liq Vol Flow [m3/h]	26.72	26.72	<empty>
Molar Enthalpy [kJ/kgmole]	-2.306e+005	-2.328e+005	<empty>
Molar Entropy [kJ/kgmole-C]	173.9	175.1	<empty>
Heat Flow [kJ/h]	-3.414e+008	-3.446e+008	3.203e+006

Name	LP STEAM	WASTE STEAM	Q-LPTURB
Vapour	1.0000	1.0000	<empty>
Temperature [C]	299.0	245.9	<empty>
Pressure [bar]	12.00	7.000	<empty>
Molar Flow [kgmole/h]	1480	1480	<empty>
Mass Flow [kg/h]	2.667e+004	2.667e+004	<empty>
Std Ideal Liq Vol Flow [m3/h]	26.72	26.72	<empty>
Molar Enthalpy [kJ/kgmole]	-2.328e+005	-2.345e+005	<empty>
Molar Entropy [kJ/kgmole-C]	175.1	176.3	<empty>
Heat Flow [kJ/h]	-3.446e+008	-3.472e+008	2.596e+006

Figure 7.11 Steam Turbines

CHAPTER 8

INSTRUMENTATION AND CONTROL LOOP

8.1 Introduction

Instrumentation and control systems are fundamental to the operation and optimization of industrial processes. These systems enable the monitoring, regulation, and optimization of industrial processes. This thesis explores the principles, components and application of instrumentation and control loops in various industrial settings.

8.2 Instrumentation

Instrumentation refers to the instruments and devices used to measure, monitor, and control physical quantities such as temperature, pressure, flow, level, and chemical composition. Common instruments include:

- Sensors and transducers: devices that convert physical quantities into electrical signals. For example, thermocouples measure temperature, and pressure transducers measure pressure.
- Transmitters: devices that send signals generated by sensors to control systems. They often convert sensor signals into standardized formats for easier processing.
- Controllers: systems or devices that receive inputs from sensors and transmitters, process this data, and make decisions to adjust process variables to desired set points. Examples include PID (Proportional-Integral-Derivative) controllers.
- Actuators: devices that execute control commands from the controllers, such as valves, motors, and relays.

8.3 Simple control loop:

A simple control loop also known as a single-loop control, is a basic control system configuration where one control loop is used to regulate the process variable. In simple control loop, there is typically one controller that receives input from sensor measuring the process variable, compares it to the set point and adjusts the manipulated variable to maintain the process variable at the desired value. For example, a level controller receives input from a level sensor, compares the measured level to the desired setpoint, and adjusts a level element to maintain the level at the required level. The main reason for using a simple control loop is to keep the process variable at the desired value efficiently.

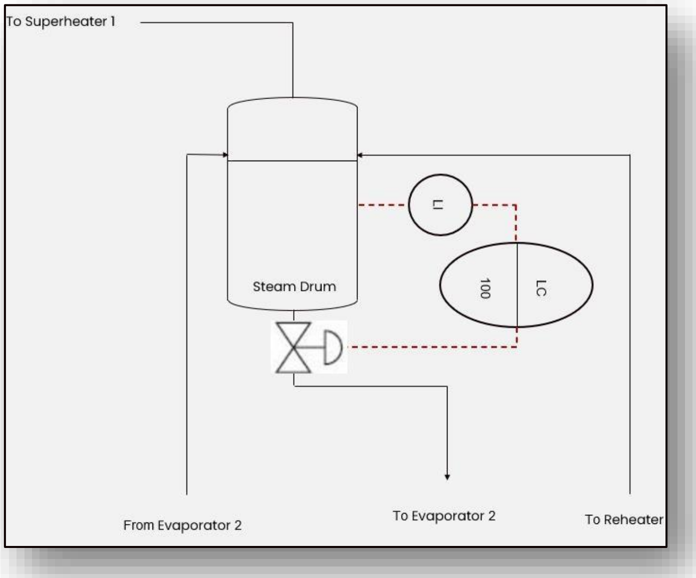


Figure 8.1 Single Level control Loop

8.4 Cascade control loop:

A cascade control loop, also called as a nested control loo, is a setup where two or more control loops are connected to enhance control performance. Typically, there are two control levels: the primary (outer) loop and the secondary (inner loop). In this system, a pressure controller acts as the primary controller, while a flowrate controller serves as the secondary controller. The desired pressure is the setpoint, and the valve adjustment is the manipulated variable. The main purpose of using a cascade loop is to keep the pressure at the desired level. By adjusting the flowrate, the system can maintain the pressure as needed. Another system example is, a temperature controller acts as the primary controller, while a flowrate controller serves as the secondary controller. The desired temperature is the setpoint, and the valve adjustment is the manipulated variable. The main purpose of using a cascade loop is to keep the temperature at the desired level. By adjusting the flowrate, the system can maintain the temperature as needed.

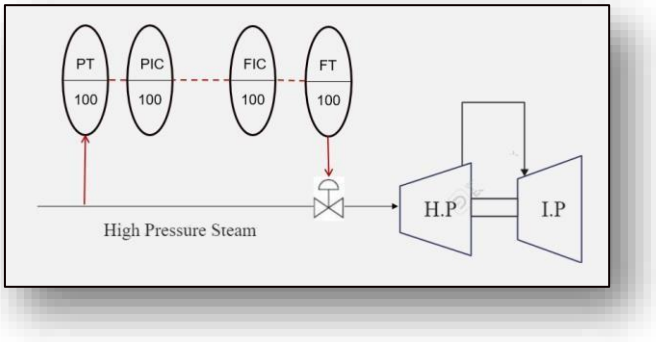


Figure 8.2 Cascade Pressure Control Loop

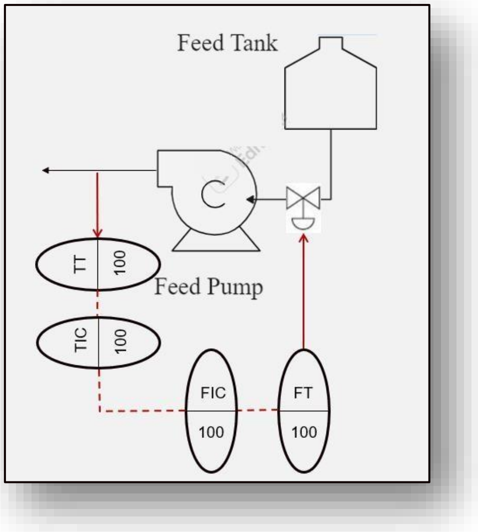
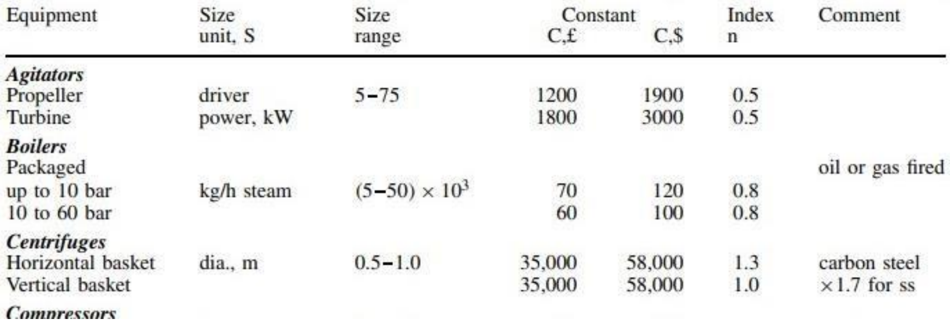


Figure 8.3 Cascade Temperature Control Loop

CHAPTER 9

ECONOMIC ANALYSIS

9.1 Purchase cost of equipment:



Equipment	Size unit, S	Size range	Constant C,£	C,$	Index n	Comment
Agitators						
Propeller	driver	5–75	1200	1900	0.5	
Turbine	power, kW		1800	3000	0.5	
Boilers						
Packaged						oil or gas fired
up to 10 bar	kg/h steam	$(5-50) \times 10^3$	70	120	0.8	
10 to 60 bar			60	100	0.8	
Centrifuges						
Horizontal basket	dia., m	0.5–1.0	35,000	58,000	1.3	carbon steel
Vertical basket			35,000	58,000	1.0	×1.7 for ss
Compressors						

Figure 9.1 Purchased Cost of Turbines

By using the formula:

$$Ce = CS^n$$

We calculated the purchased cost of turbines:

Table 9.1 Purchased cost of Turbines

HP - Turbine	$ 83812
Intermediate- Turbine 1	$ 81884
Intermediate- Turbine 2	$ 89548
LP- Turbine	$ 80582
Gas Turbine	$ 752994

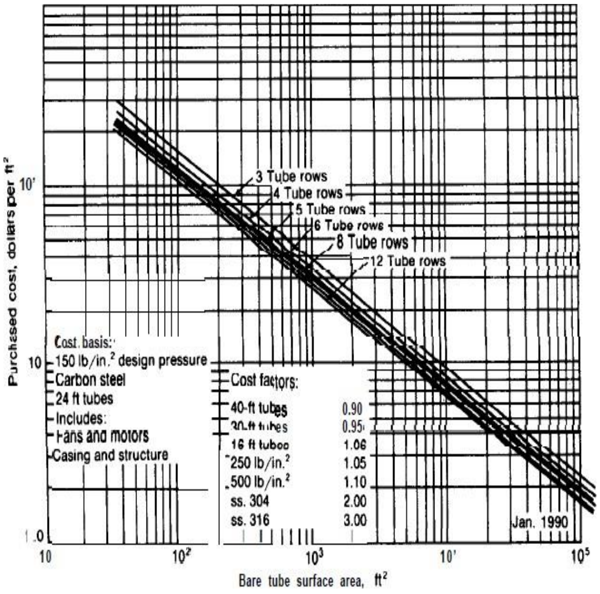


Figure 9.2 Purchased Cost of Condenser

By using the graph above we calculated the purchased cost of condensers for 12 tube rows:

Table 9.2 Purchased cost of Condensers

Condenser 1	$ 16000
Condenser 2	$ 16000

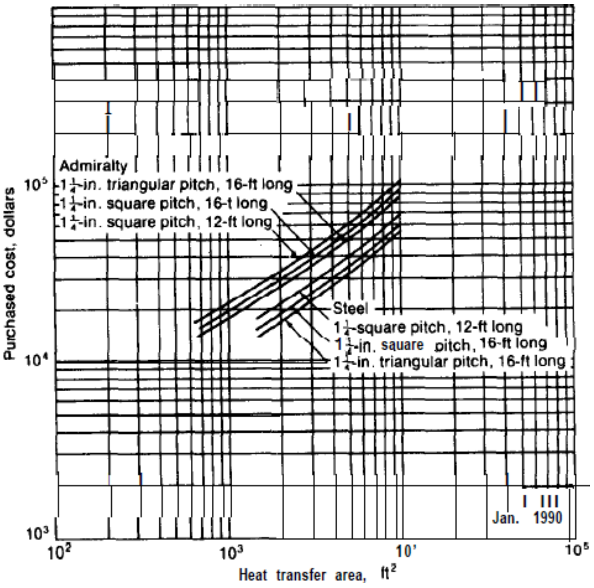


Figure 9.3 Purchased Cost of Fin Tube heat exchanger

By using the graph above we calculated the purchased cost of fin tube heat exchangers for carbon steel material 1 ½ triangular pitch, 16 ft-long:

Table 9.3 Purchased cost of Fin tube heat exchangers

Economizer 1	$ 14000
Economizer 2	$ 13000
Evaporator 1	$ 15000
Evaporator 2	$ 11000
Reheater	$ 14800
Superheater 1	$ 13900
Superheater 2	$ 12500
Total Purchase Cost	$ 94200

The steam drum and pumps were also calculated from literature which turned out to be:

Table 9.4 Purchased cost of Steam drum and pump

Steam Drum	$ 30800
Pump	$ 150000

Total Purchased Cost of Equipment:

In 2004 = $ 1.42 M

In 2024 = $ 2.50 M

9.2 Physical Plant Cost:

Factors involved here include:

Table 9.5 Factors for Physical Plant cost

f1 (Equipment Erection)	0.4
f2 (Piping)	0.7
f3 (Instrumentation)	0.2
f4 (Electrical)	0.1
f6 (Utilities)	0.5

Physical Plant Cost = Purchased Cost of Equipment (1+f1+ f2…..+f6)

= $ 7.24 M

9.3 Fixed Capital Cost:

Factors involved here include:

Table 9.6 Factors for Fixed Capital cost

f10 (Design and Engineering)	0.3
f11 (Contractor Fee)	0
f12 (Contingency)	0.1

Fixed Capital Cost = Physical Plant Cost (1 + f10 + f11 + f12)

= $ 10.14 M

Working Capital = 5% of Fixed Capital = **$ 5.07 lac**

Total Initial Investment = Fixed Capital + Working Capital

= $ 10.65 M

9.4 Fixed Operating Cost:

Factors involved here include:

Table 9.7 Factors for Fixed Operating cost

Maintenance (5-10 per cent of fixed capital)	$ 452684
Operating Labor	$ 20000
Laboratory Cost (20% of the Laboure´ cost)	$ 6000
Supervision (20% of the Laboure´ cost)	$ 6,400
Plant overheads (50% of Laboure cost)	$ 3000

Fixed Cost = **$ 5.36 lac**

9.5 Overall Production Cost:

Factors involved here include:

Table 9.8 Factors for Overall Production cost

Miscellaneous Materials (10% of maintenance cost)	$ 50718
Variable cost = Miscellaneous Materials	$ 50718

Overall Production Cost = Fixed Cost + Variable Cost

= **$ 5.87 lac**

CHAPTER 10

HAZOP ANALYSIS

10.1 Introduction

Hazard and Operability analysis, or HAZOP, is a thorough and systematic technique to perform risk assessment in a structured manner and identify potential hazards that could lead to catastrophic and critical hazards and incidents. Employee's well-being is of great importance with the maintenance of plant' safety and efficiency. By using different procedures, HAZOP helps ensure reliable production of needed products, which in turn boost profitability.

10.2 Hazard Identification:

The following techniques are included in Hazard Identification:

- **Safety reviews**

  A safety review is the thorough check of a worksite to find risks and safety issues. It also looks at how effective the company's safety measures and programs are.
- **Hazard Surveys**

  A hazardous material survey involves checking buildings and structures for harmful materials that could affect the health of workers, people insides, or the environment, and then creating a report on findings.
- **Hazard and Operability Studies**

  Participants suggest different events that could happen to a specific piece of equipment. They then decide if and how each event could occur and whether it poses any risk. This process is crucial for consistently producing the desired product, which in turn will increase the profitability of the process.

- **Process Hazard Checklists**

  A process hazard checklist is a list of potential problems in a process that need to be reviewed during hazard assessments. The main goal of this checklist is to identify possible health and safety risks by examining workplace policies and procedures.

10.3 Health and Safety Communication:

- All employees regularly receive training on preventing risks and staying safe at work.
- Hazard safety signs are installed according to international and national standards.
- All equipment should be correctly labeled and tagged.
- Different areas of plants and walkways are correctly marked.
- Instruction manuals for all equipment must be available.
- There is an access point for material safety data sheets.

10.4 HAZOP on Heat Recovery Steam Generator:

Table 10.1 HAZOP on HRSG

Parameter	Guide word	Deviation	Causes	Consequences	Action
Steam Flow	**Less**	Less flow of steam in HRSG	Insufficient feedwater flow Leakage in steam Flow pipes	Loss of revenue Risk of overheating Reduced power generation	Inspect and repair any leaks Maintain feedwater pumps.

	More	More than optimal steam flow to HRSG	Higher than expected heat input from the gas turbine exhaust	Overload on downstream equipment. Water carryover	Installation of flow control devices. Monitoring of steam flow rates
	Reverse	Black flow of steam due to high back pressure	Control system failure. Valve malfunctioning	No heat exchange	Installation of automatic sensors and control devices. Installation of Non-Return Valves
Temperature	**High**	High Temperature	Excessive steam flow	Risk of overheating HRSG components	Optimize combustion parameters. Implement automatic temperature control systems.

	Low	Low Temperature	Low steam flow Fluctuations in steam pressure	Potential for water condensation Corrosion	Implement heat tracing. Monitor steam quality
Pressure	**High**	High Pressure	Inadequate condensate removal from steam drum.	Risk of over pressure leading to equipment damage	Pressure sensors with alarm. Installation of pressure relief valves
	Low	Low Pressure	Steam leaks. Underperformance of feedwater pump	Decreased power output. Operational instability	Check for leakages. Adjust gas turbine output. Monitor steam quality.

10.5 HAZOP on Gas Turbine Generator:

Table 10.2 HAZOP on GTG

Parameter	Guide word	Deviation	Causes	Consequences	Action
Flow	**No**	No flow in GTG	Failure in inlet air system Manual valve closed	Loss of revenue Immediate reduction in power generation	Emergency shutdown
	Less	Less than optimal flow to GTG	Line blockage. Leakages in air intake system	Fluctuations in performance	Installation of flow control devices.
Temperature	**High**	High Temperature	Combustion chamber malfunctioning leading to excessive heat generation	Wear and tear of turbine components	Install high temperature alarms and air coolers.
	Low	Low Temperature	Heat leaks. Insufficient air flow	Reduced thermal efficiency. Increased emission	Adjust air flow rates and fuel air ratio
Pressure	**High**	High Pressure	Excessive fuel flow	Increased stressed on compressor.	High pressure sensors with alarm

				Reduced efficiency	
	Low	Low Pressure	Inadequate compressor Leaks and blockages in fuel supply system	Flame out. Turbine trips Reduced power output	Regular maintenance schedule Installation of pressure sensors

10.6 HAZOP on Steam Turbine:

Table 10.3 HAZOP on Steam Turbines

Parameter	Guide word	Deviation	Causes	Consequences	Action
Steam Flow	**Less**	Less flow of gas in Heat exchanger	Reduced steam generation	Low power output Efficiency reduction	Check bypass valves. Inspect turbine control system.
	More	More than optimal flow to Heat Exchanger	Mechanical failure Control system malfunctioning	Equipment damage Process instability	Repair or maintenance. Control system adjustment.
Temperature	**High**	High Temp	Fouling and scaling on turbine blades	Elevated risk of steam leaks and	Adjust steam flowrates

				turbine blades damage	through control valves. Maintenance procedures
	Low	Low Temp	Leaks in steam lines causing heat loss Reduced heat from the HRSG	Risk of condensation within turbine Reduced power output	Replace malfunctioning temperature sensors. Monitor feedwater system
Pressure	**High**	High Pressure	Fouling in steam pathways Overfeeding of water into the HRSG	Damage to turbine components Instability in turbine operation	Adjust flow rates Repair pressure sensors Inspect and clear any blockages
	Low	Low Pressure	Blockages in the steam lines Poor performance of the condenser	Impact on overall plant productivity Risk of turbine trip	Clear any blockages in the steam piping Replace malfunctioning control valves

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