POWER PLANT ENGINEERING

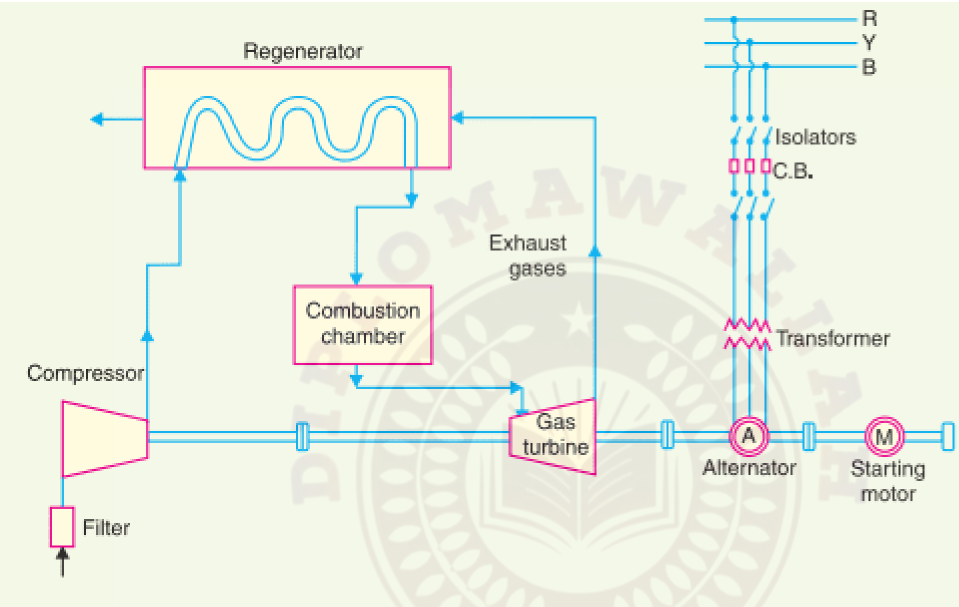
DIPLOMA WALLAH

MECHANICAL

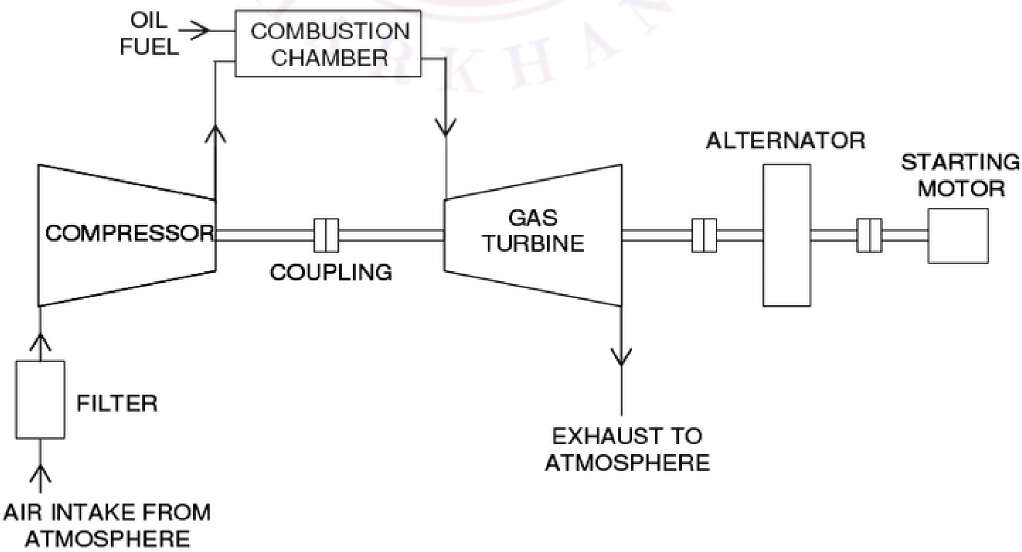
Jharkhand University Of Technology (JUT)

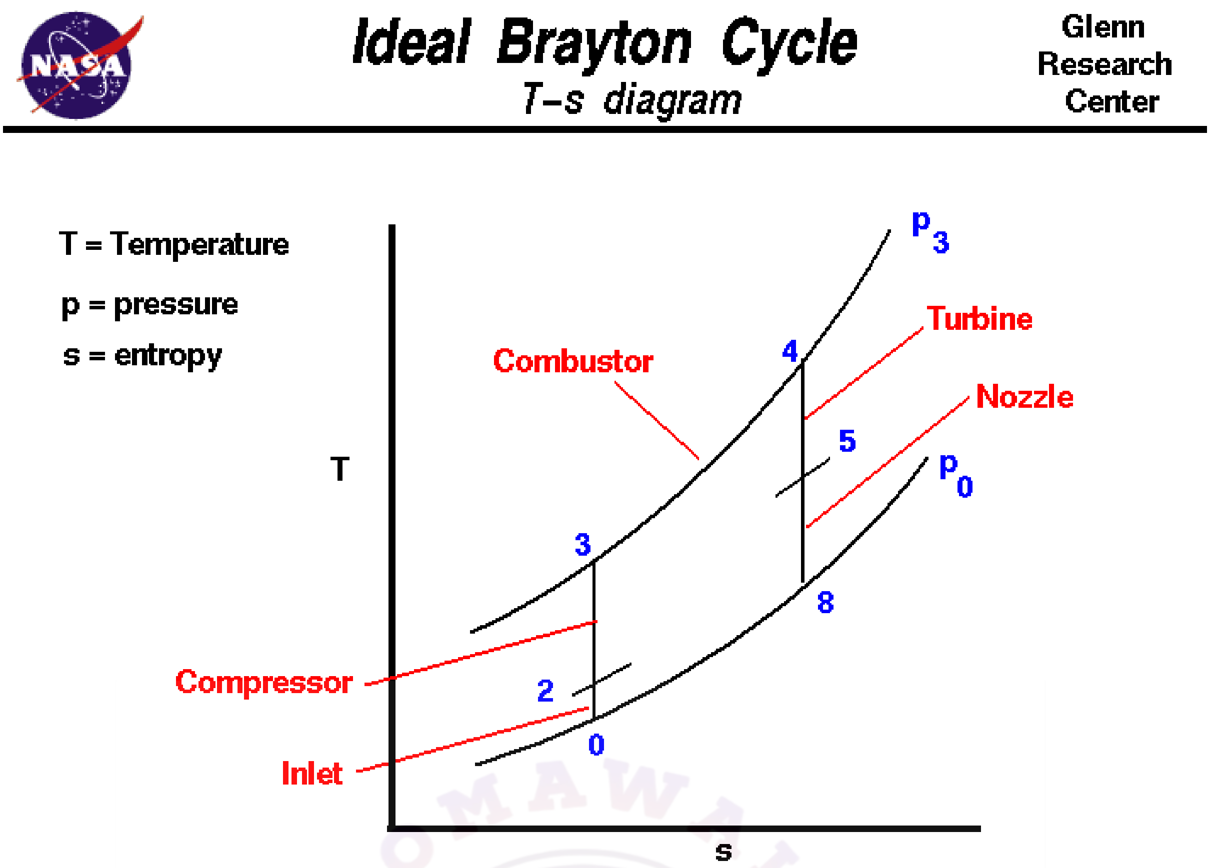
Unit - III Gas Power Plant and Waste Heat Recovery

3.1 Introduction to Gas Turbine Power Plant, Concept of Brayton cycle



Schematic arrangement of gas turbine power plant.




Ideal Brayton Cycle
T-s diagram
Glenn
Research
Center
T = Temperature
p = pressure
s = entropy
T
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Combustor
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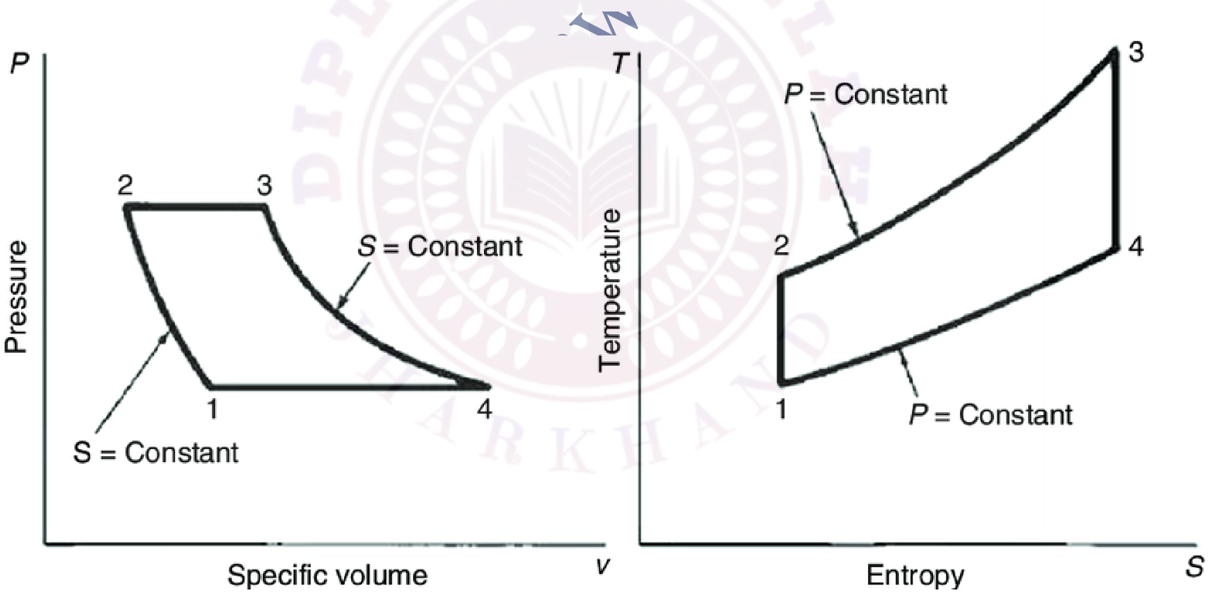
P
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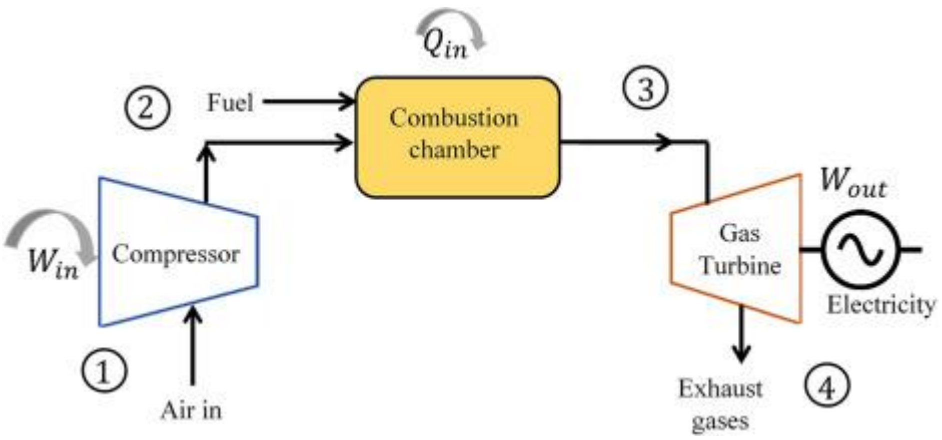


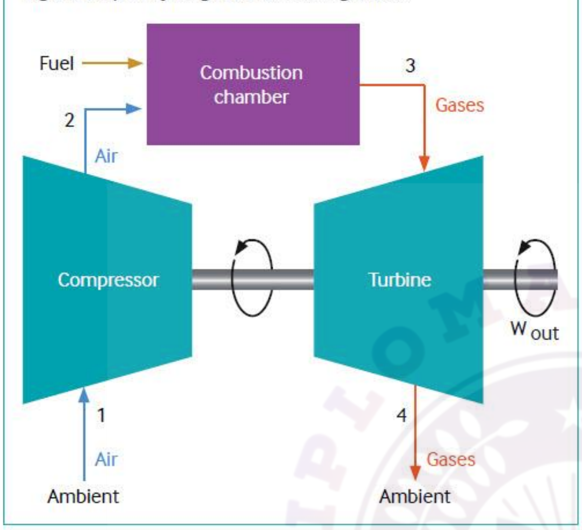


Figure 1: Open-cycle gas turbine configuration

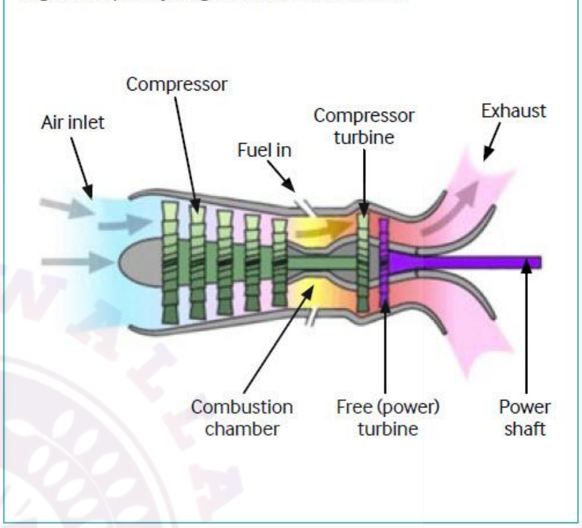


Figure 2: Open-cycle gas turbine cross-section

3.1.1 What is a Gas Turbine Power Plant?

A **gas turbine power plant** is a generating station where a gas turbine (instead of a steam turbine used in traditional thermal plants) is the prime mover for producing electricity. The plant draws in ambient air, compresses it, mixes it with fuel (natural gas, diesel or other gaseous fuel), burns this mixture in a combustion chamber, and then expands the hot combustion products through a turbine. The turbine drives a generator to produce electricity, and part of the turbine work drives the compressor.

This type of plant is often chosen because it can start quickly, has a smaller footprint, and uses simpler systems compared to large boiler-steam plants.

3.1.2 Concept of the Brayton Cycle

The Brayton cycle (also known as the Joule cycle) is the thermodynamic idealisation of how a gas turbine power plant works. It consists of four main processes (for the ideal open cycle) as follows:

1. **Compression (isentropic idealisation)**: Ambient air is drawn in and compressed to a higher pressure and temperature. (Wikipedia)
2. **Heat addition at constant pressure (isobaric process)**: The compressed air is mixed with fuel and combusted; the pressure remains (ideally) constant while the temperature rises significantly. (NASA Glenn Research Center)
3. **Expansion (isentropic idealisation)**: The high-temperature, high-pressure gases expand through the turbine, producing work. Some of that work drives the compressor; the remainder drives the generator.
4. **Heat rejection at constant pressure**: The exhaust gases are released to the atmosphere (or heat sink) at approximately constant pressure, completing the cycle.

On a T-s or p-v diagram, the Brayton cycle shows the compression leg, the heat-addition leg, the expansion leg and the heat rejection leg. (NASA Glenn Research Center)
Key insight: The efficiency of the ideal Brayton cycle can be expressed (in simplified form) as:
[
\eta = 1 - \left(\frac{P_1}{P_2}\right)^{(\gamma -1)/\gamma}
]
where (P_1) & (P_2) are the pressures before and after compression, and (\gamma) is the specific heat ratio. (Wikipedia)
From this relation, increasing the pressure ratio (i.e., achieving higher (P_2/P_1)) improves thermal efficiency. (Massachusetts Institute of Technology)

3.1.3 Why it matters in Power Plant Engineering

- Because the Brayton cycle is the underlying thermodynamic principle, you as a student must understand:
  - How compressor pressure ratio, turbine inlet temperature, and exhaust conditions affect output and efficiency.
  - That practical plants deviate from ideal: real compressors/turbines have inefficiencies, pressure drops, heat losses.

- The simpler layout of a gas turbine plant versus a steam-plant makes maintenance, start-up/shutdown faster—important when you study "modern power plant" operations.
- For the course outcome CO3 ("Use knowledge and skills related to Gas Power Plant and Waste Heat Recovery properly in a given situation"), the gas turbine plant is a core topic. Knowing its theory, components, layout and advantages/disadvantages is essential.

3.1.4 Important Points to Note

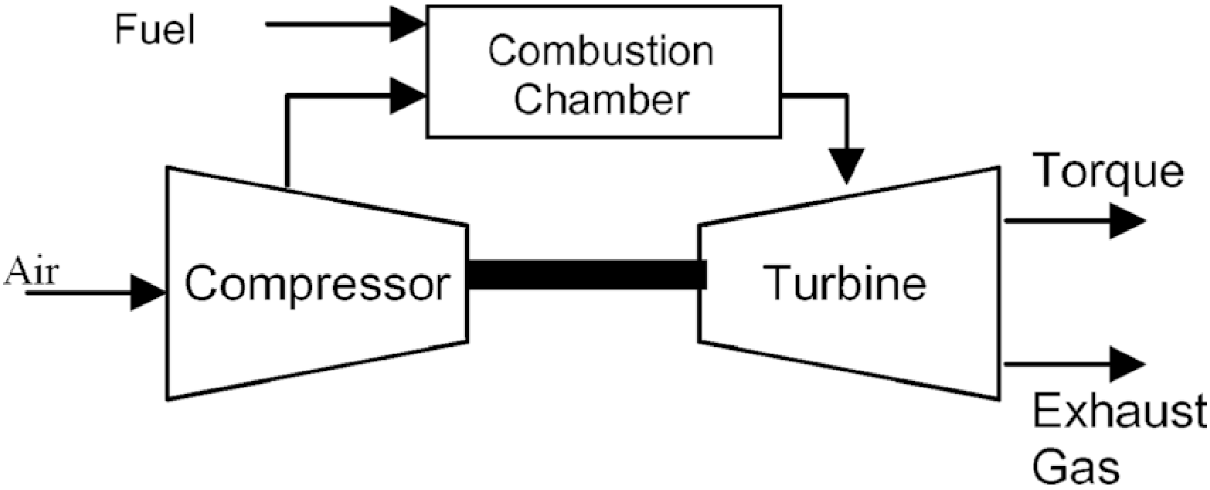
- Although the Brayton cycle gives a theoretical efficiency, real plants have lower efficiency due to losses (compressor/turbine inefficiency, heat losses, exhaust losses). (Simon Fraser University)
- Gas turbine plants are often used for **peaking** or **intermediate** load because they can ramp fast, though combined-cycle versions (with Steam cycle added) are used for more baseload duty.
- The simple open-cycle gas turbine often has lower efficiency compared to a steam cycle plant, but its advantages include smaller size, simpler systems, quicker start-up.
- Exhaust gases of a gas turbine still carry substantial heat — which leads to the concept of **waste heat recovery** (covered in later units) and **combined/closed cycle** configurations.

3.1.5 Summary

In summary, Section 3.1 introduces you to:

- The concept and layout of a gas turbine power plant.
- The thermodynamic basis (Brayton cycle) which governs its operation.
- How the cycle components (compressor, combustion chamber, turbine) map onto the real plant.
- Why it's a relevant choice in modern power generation, especially where flexibility, rapid start-up or waste-heat recovery are important.

Section 3.2 — Arrangement of Open and Closed Cycles with Constant-Pressure Gas Turbine Power Plant



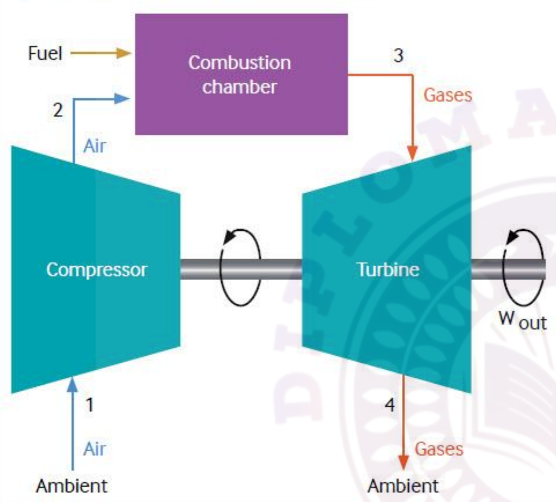


Figure 1: Open-cycle gas turbine configuration

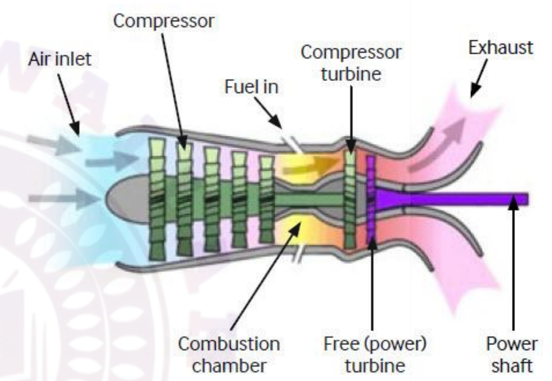
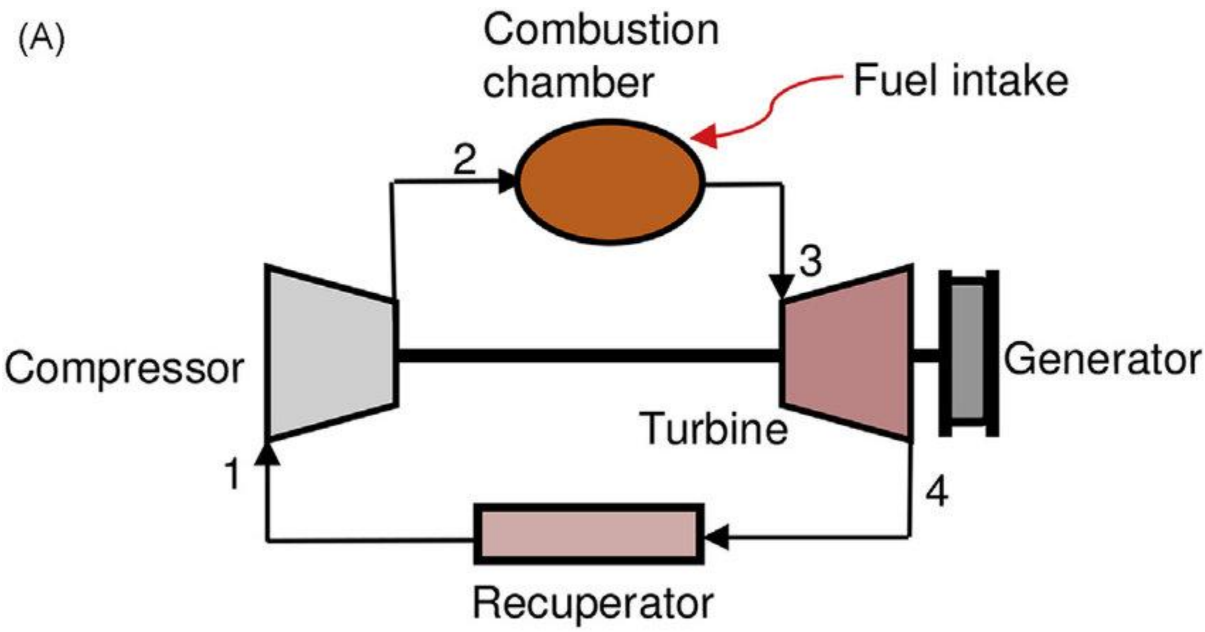
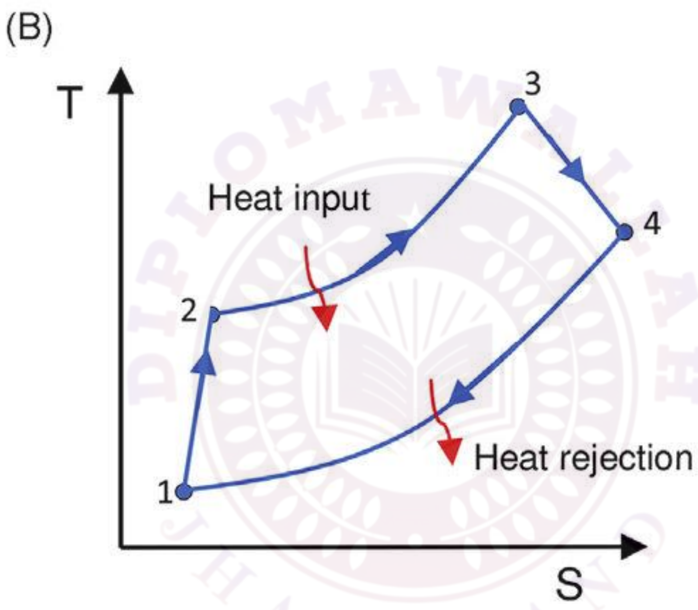


Figure 2: Open-cycle gas turbine cross-section


(A)
Combustion chamber
Fuel intake
2
3
Compressor
Generator
Turbine
1
4
Recuperator


(B)
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Heat input
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Heat rejection
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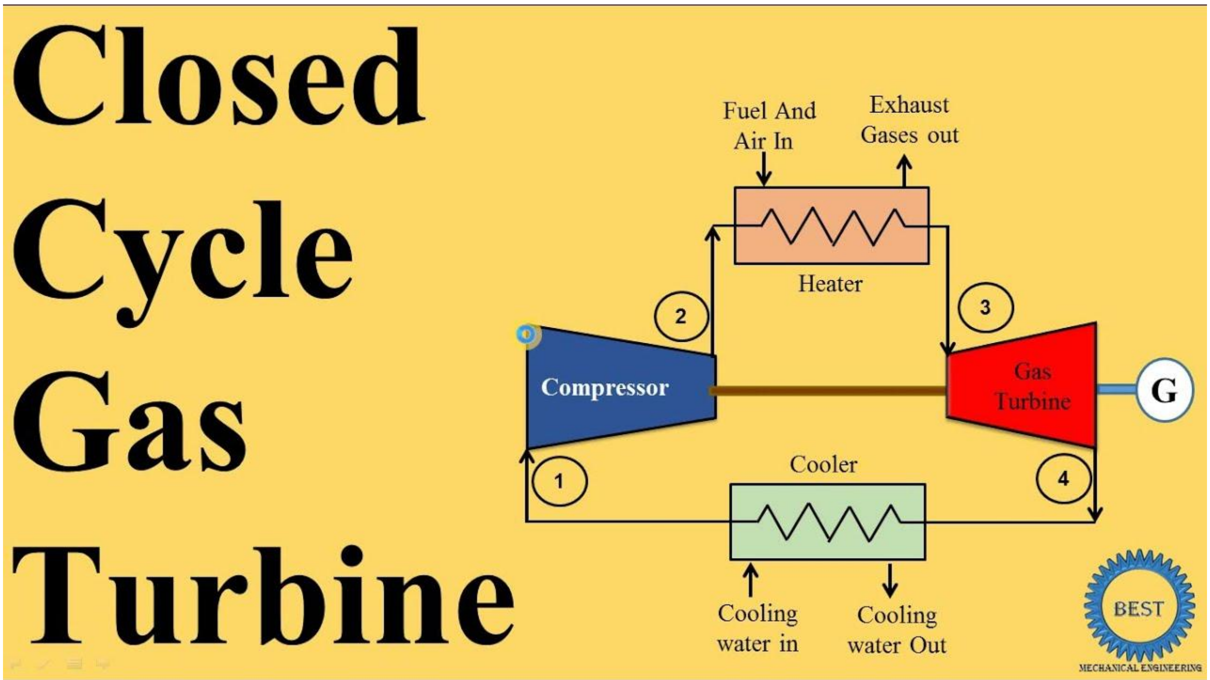
Closed
Cycle
Gas
Turbine
Fuel And
Air In
Exhaust
Gases out
Heater
2
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BEST
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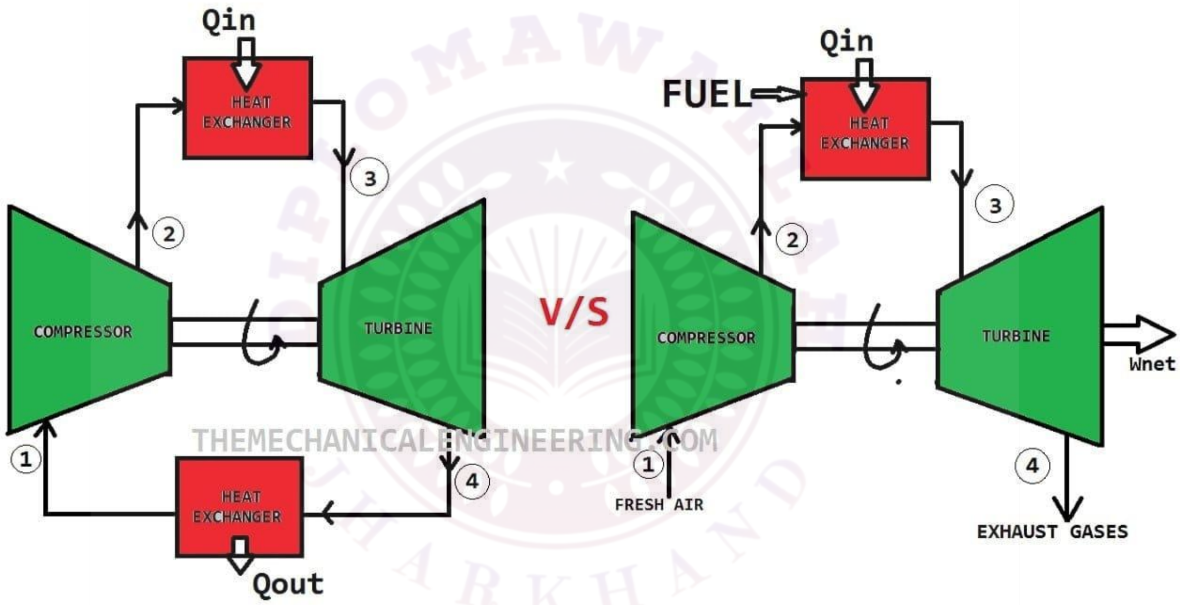
Qin
HEAT
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COMPRESSOR
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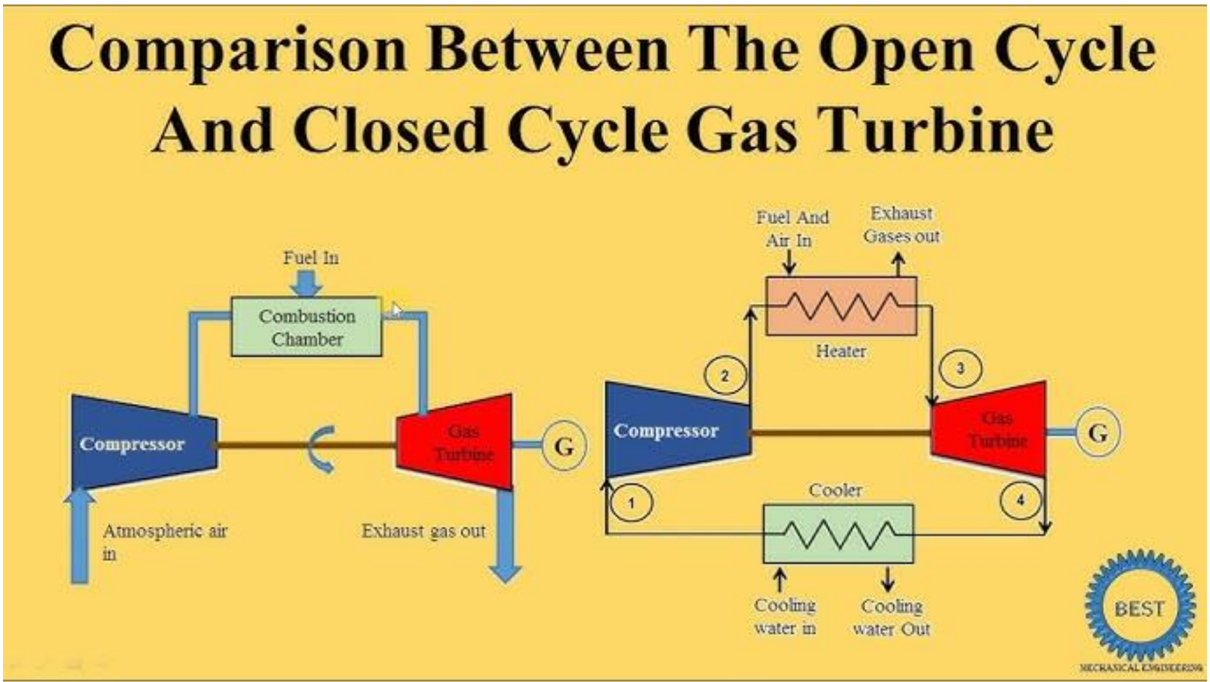
EXHAUST GASES
THEMECHANICALENGINEERING.COM


Comparison Between The Open Cycle And Closed Cycle Gas Turbine
Fuel In
Combustion Chamber
Compressor
Gas Turbine
G
Atmospheric air in
Exhaust gas out
Fuel And Air In
Exhaust Gases out
Heater
2
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Compressor
Gas Turbine
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Cooler
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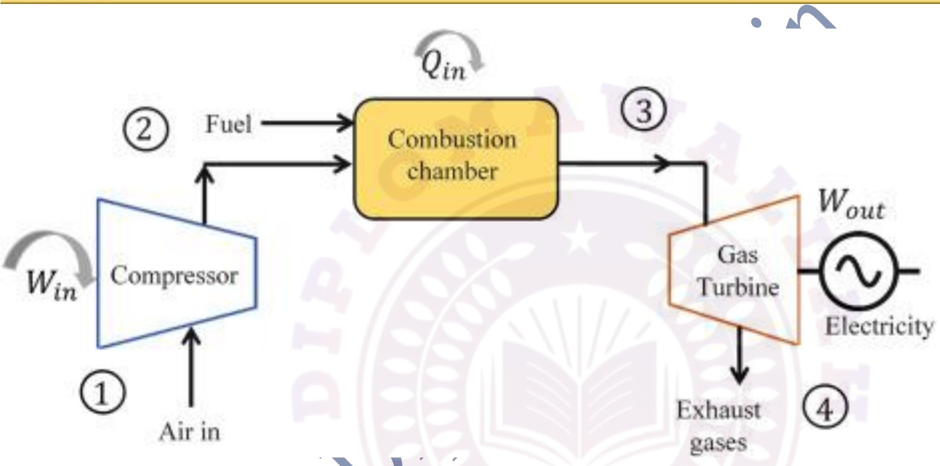
Cooling water in
Cooling water Out
BEST
MECHANICAL ENGINEERING


Q_{in}
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Fuel
Combustion chamber
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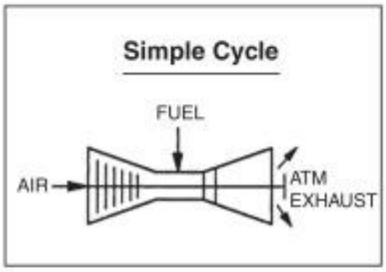
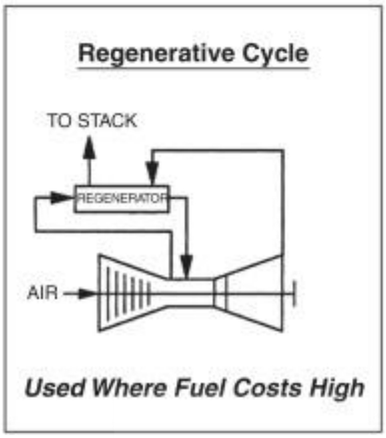
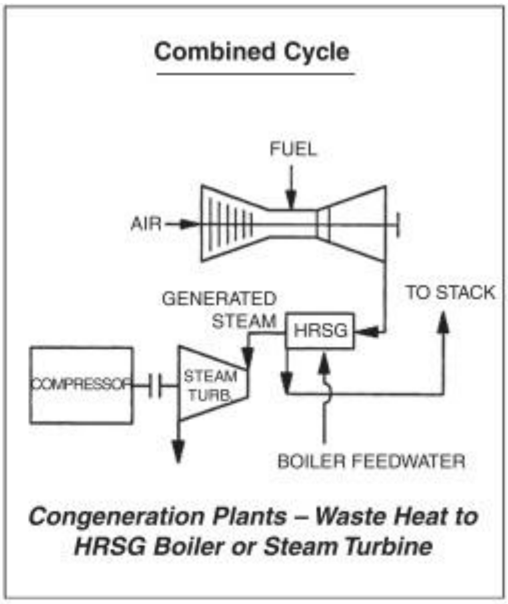
W_{out}
W_{in}
Compressor
Gas Turbine
Electricity
1
Air in
Exhaust gases
4





Used Where Fuel Costs High



Congeneration Plants – Waste Heat to HRSG Boiler or Steam Turbine

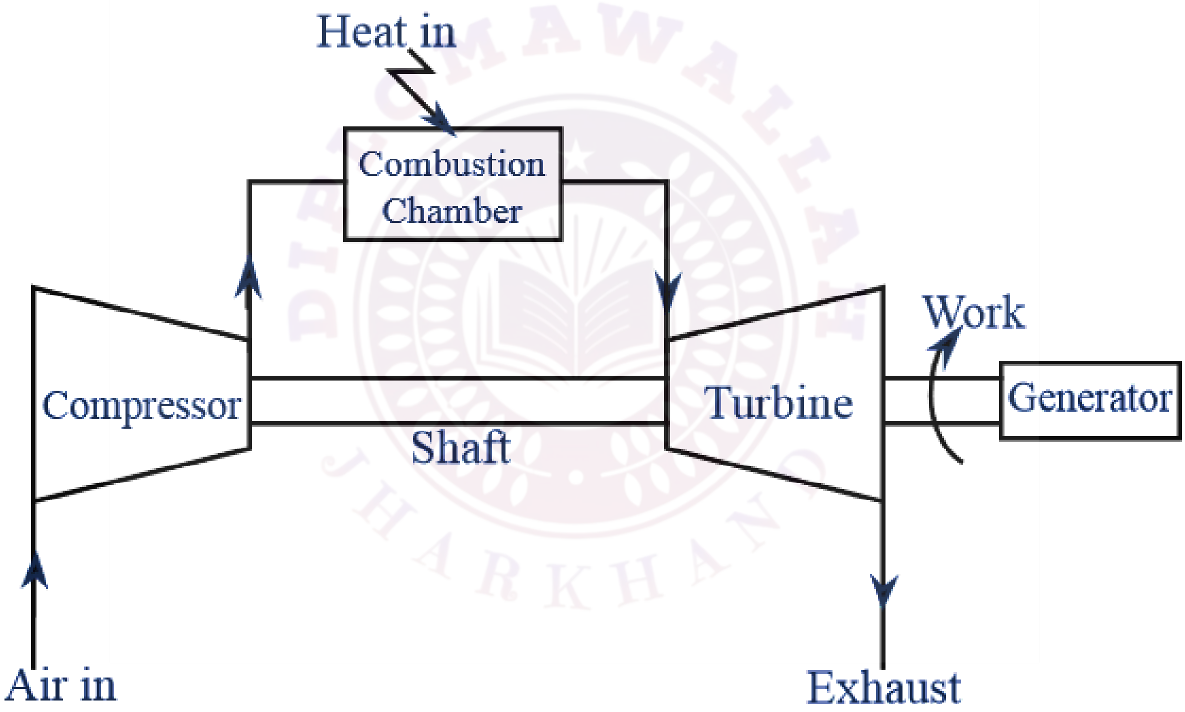
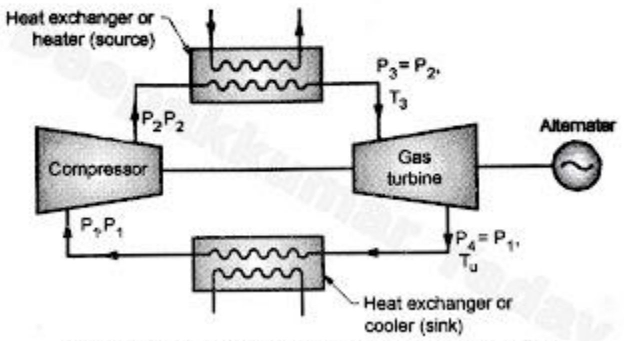


Figure (1) : Open Cycle Gas Turbine



Schematic Diagram of Closed cycle Gas Turbine Power Plant

3.2.1 Definitions & Fundamental Concepts

- A **constant-pressure gas turbine power plant** is one where the heat addition to the working fluid occurs at roughly constant pressure (typical of the Brayton cycle). In such plants, the cycle comprises compression, heat addition at constant pressure, expansion through turbine, heat rejection or exhaust. (Nuclear Power)
- **Open-cycle gas turbine plant**: Ambient air is drawn in, compressed, fuel is burnt in the compressed air, the hot gases expand through the turbine to produce work, and the exhaust gases are released to the atmosphere (not reused). (TutorialsPoint)
- **Closed-cycle gas turbine plant**: A working fluid (air, helium, nitrogen, CO_2, etc.) circulates in a closed loop: compressed, heated either via an external heat exchanger or combustion separate from the working fluid, expanded in a turbine, cooled and returned to the compressor—no direct exhaust to atmosphere of working fluid. (ElProCus)

3.2.2 Arrangement of Open Cycle (Constant Pressure Gas Turbine)

Schematic & Workflow

- Components: compressor → combustion chamber (constant pressure) → turbine → exhaust to atmosphere.
- Workflow:

1. Draw in ambient air → compressor (increases pressure & temperature).
2. Compressed air enters combustion chamber where fuel is injected and burnt; because pressure is maintained (or small drop) the process approximates constant pressure heat addition.
3. Hot high-pressure combustion gases expand through turbine → do work (part drives compressor, remainder drives generator/load).
4. Exhaust gases are released into atmosphere, completing the cycle. (TutorialsPoint)

Key Features

- Simpler plant layout (fewer heat-exchangers, fewer loops).
- Quicker start up, compact footprint (useful for peaking or mobile applications).
- Working fluid is ambient air + combustion products; large volume flow.
- Thermal efficiency is lower compared to more complex cycles because much heat leaves in exhaust.

Engineering Notes

- Because heat addition is at constant pressure, the cycle matches the ideal Brayton cycle approximation—but real losses (compressor/turbine inefficiency, pressure drop, heat losses) reduce performance.
- Ambient conditions (temperature, pressure) strongly affect performance; hot ambient reduces compressor efficiency → lowers output.
- Exhaust gas temperature remains significant: opportunity for heat recovery (e.g., HRSG) or waste heat utilisation.

3.2.3 Arrangement of Closed Cycle (Constant Pressure Gas Turbine)

Schematic & Workflow

- Components: compressor → external heater/heat exchanger → turbine → cooler / heat-rejector → back to compressor.
- Workflow:
    1. Working fluid (air, nitrogen, helium etc) is compressed.
    2. Compressed fluid is heated via an external heat source (combustion, nuclear, solar) at approximately constant pressure.
    3. Heated fluid expands through turbine → produces work.
    4. After expansion, fluid passes through cooler (or recuperator) to reject heat, then returns to compressor, completing loop. (ElProCus)

Key Features

- Working fluid is confined; no mixing with ambient or combustion products (unless fuel combustion is external).
- Can use optimal working fluids (helium, CO_2) and materials because no direct contact with combustion impurities.
- Higher potential thermal efficiency since fluid properties, recuperation, high pressures/temperatures can be optimised.
- More complex plant: heat exchangers, seals, closed loop control, higher capital cost, more maintenance.

Engineering Notes

- Because the working fluid is recirculated, mass flow is steady and known, enabling more controlled design of turbine/compressor.
- Heat rejection via cooler or recuperator can reduce exhaust losses, improve cycle efficiency.
- Suitable for high-temperature applications, closed nuclear reactors, specialised gas turbine applications.
- For mechanical/plant engineers: maintenance of loop integrity, seals, external heaters, cooling/reheating circuits becomes critical.

3.2.4 Comparison of Open vs Closed Cycles

Parameter	Open Cycle	Closed Cycle
Working fluid	Ambient air + combustion products, exhausted	Fixed working fluid recirculated
Complexity	Relatively simple	More complex (heat exchangers, loops, seals)
Thermal efficiency	Lower (without heat recovery)	Higher potential (with recuperation, ideal design)
Capital cost & maintenance	Lower cost, simpler maintenance	Higher cost, more complex maintenance
Suitability	Peaking plants, rapid start, smaller size	Large stationary plants, high efficiency priority
Exhaust handling	Direct exhaust to atmosphere	No direct exhaust (in closed loop)
Working fluid contamination	Combustion products contact turbine blades	Cleaner environment for turbine materials

This table is supported by references. (themechanicalengineering.com)

3.2.5 Engineering Implications for Power Plant Design & Operation

- **Choice of cycle (open vs closed)** influences equipment design (compressor/turbine), materials (blade life, corrosion), auxiliary systems (cooling, heat exchangers), plant layout, start-up behaviour and maintenance strategies.
- For a given application (e.g., base load vs peaking), one must weigh efficiency vs cost vs complexity: open cycles may suffice where rapid response is needed; closed cycles may be justified where high efficiency and long-term cost savings matter.
- **Heat recovery potential**: In open cycles, exhaust losses are high → utilising exhaust heat via a combined cycle or HRSG can improve overall efficiency. These link to later units on waste heat recovery.

- **Ambient conditions**: Open cycle performance drops more with ambient temperature; closed cycle more controllable but requires more sophisticated design.
- **Maintenance & life-cycle cost**: Closed loops require attention on loop sealing, heat-exchanger cleaning/fouling; open cycles may face higher blade erosion/corrosion due to combustion products.
- **Fuel flexibility**: Because closed cycles use a separate working fluid and external heater, they can use different heat sources (solar, nuclear) more easily; open cycles are tied to combustion of fuel in the working fluid.

3.2.6 Summary

In summary:

- This section covers two fundamental arrangements of gas turbine power plants under constant-pressure heat addition: open and closed cycles.
- Understanding their layouts, operational differences, pros/cons, and engineering trade-offs is essential for designing, operating, maintaining, and choosing appropriate gas turbine power plants (which links directly to your syllabus CO3).
- Make sure when you refer to component lists, operational parameters (compressor pressure ratio, turbine inlet temperature, cycle efficiency), you link back to whether it's open or closed cycle—because the differences in fluid flows, exhaust, loop configuration significantly affect design/maintenance.

3.3 Components of a Gas Turbine Power Plant and Their Function

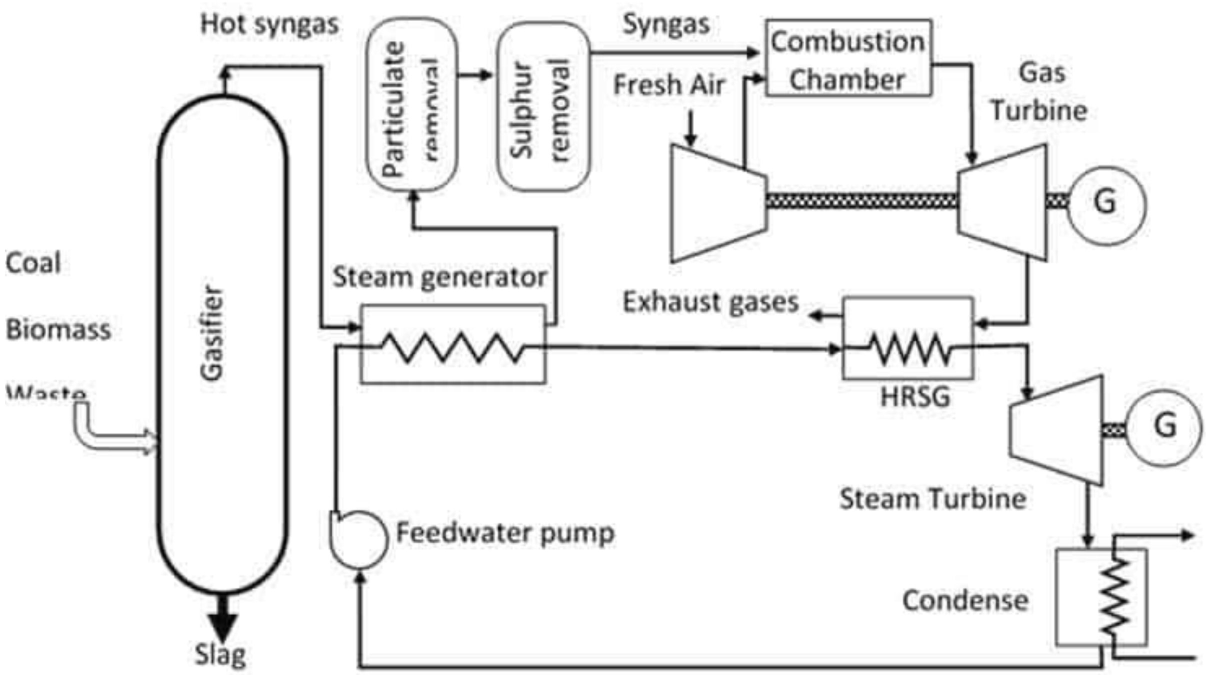
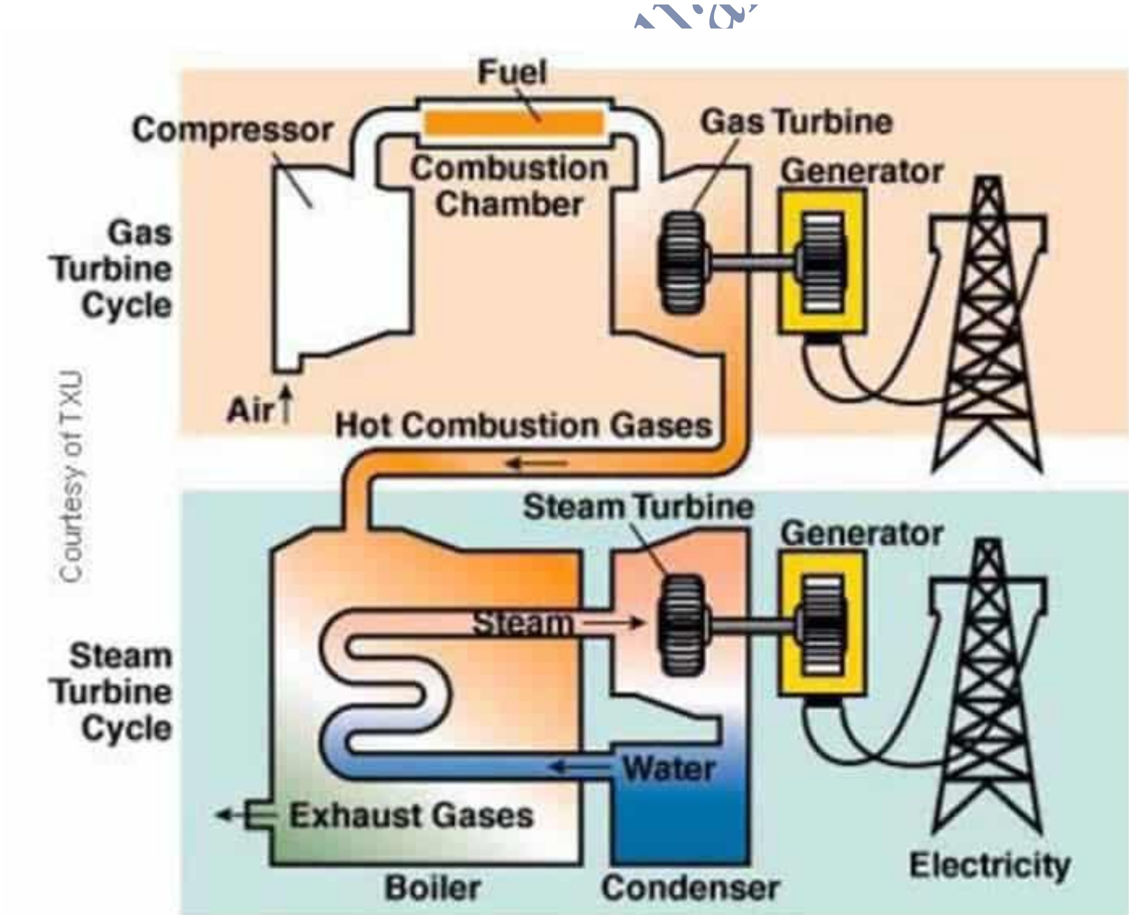
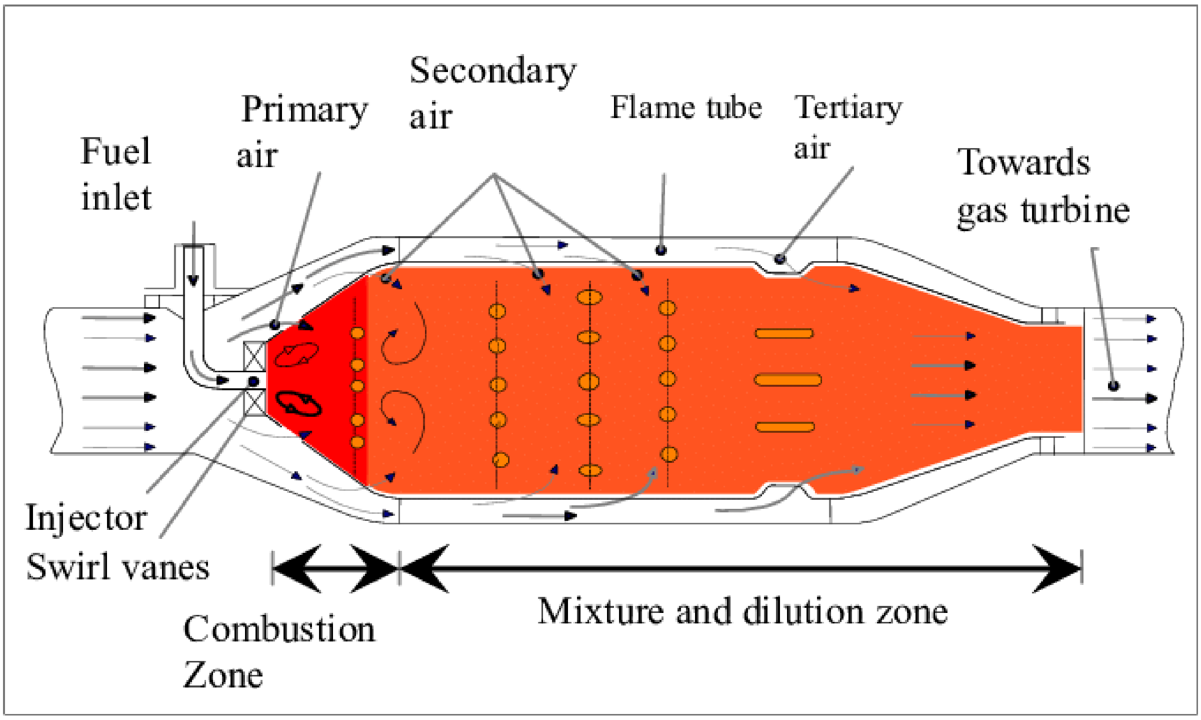
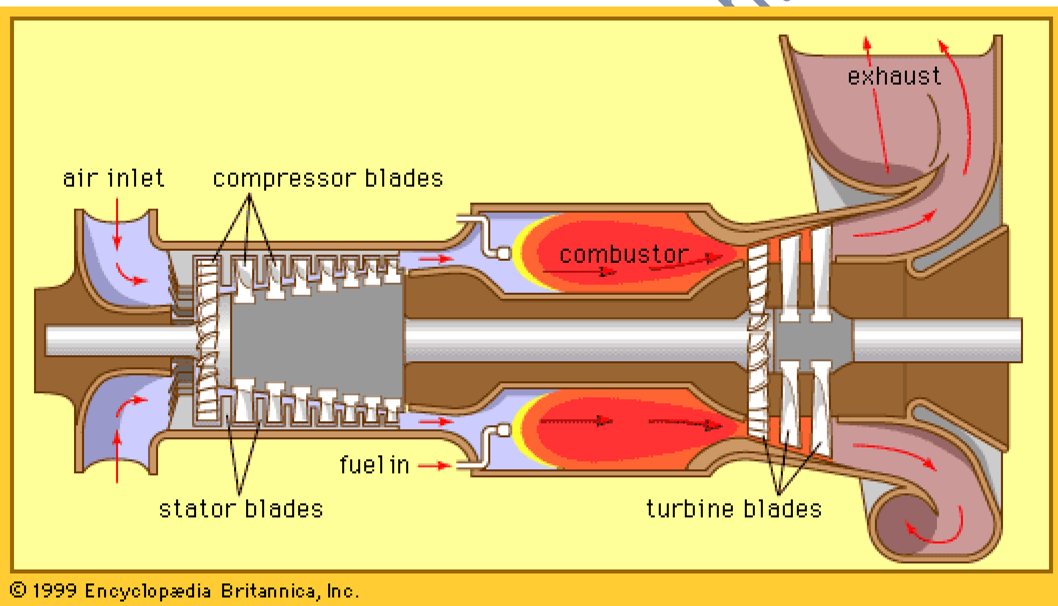
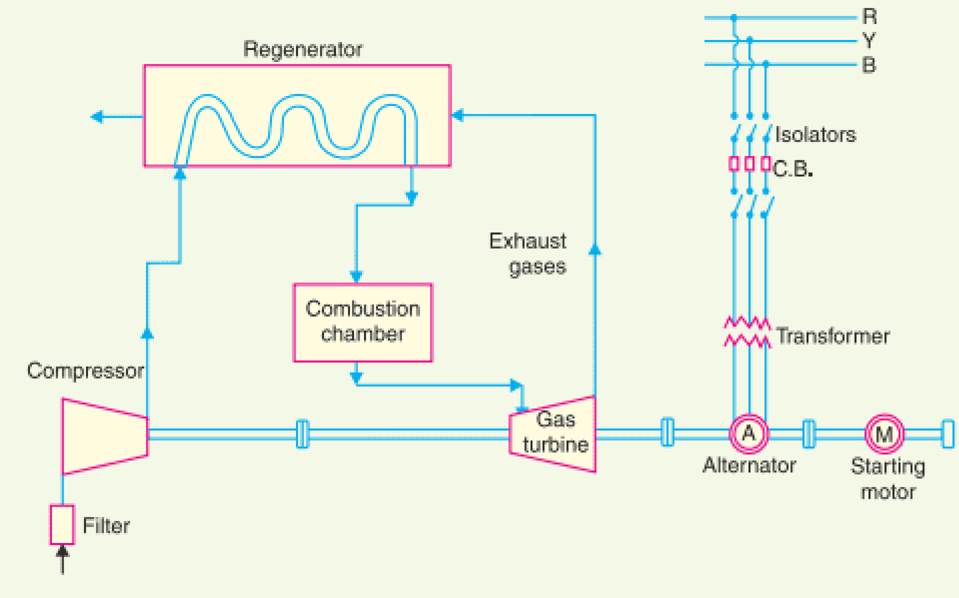


Figure 6.7. Schematic diagram of IGCC.

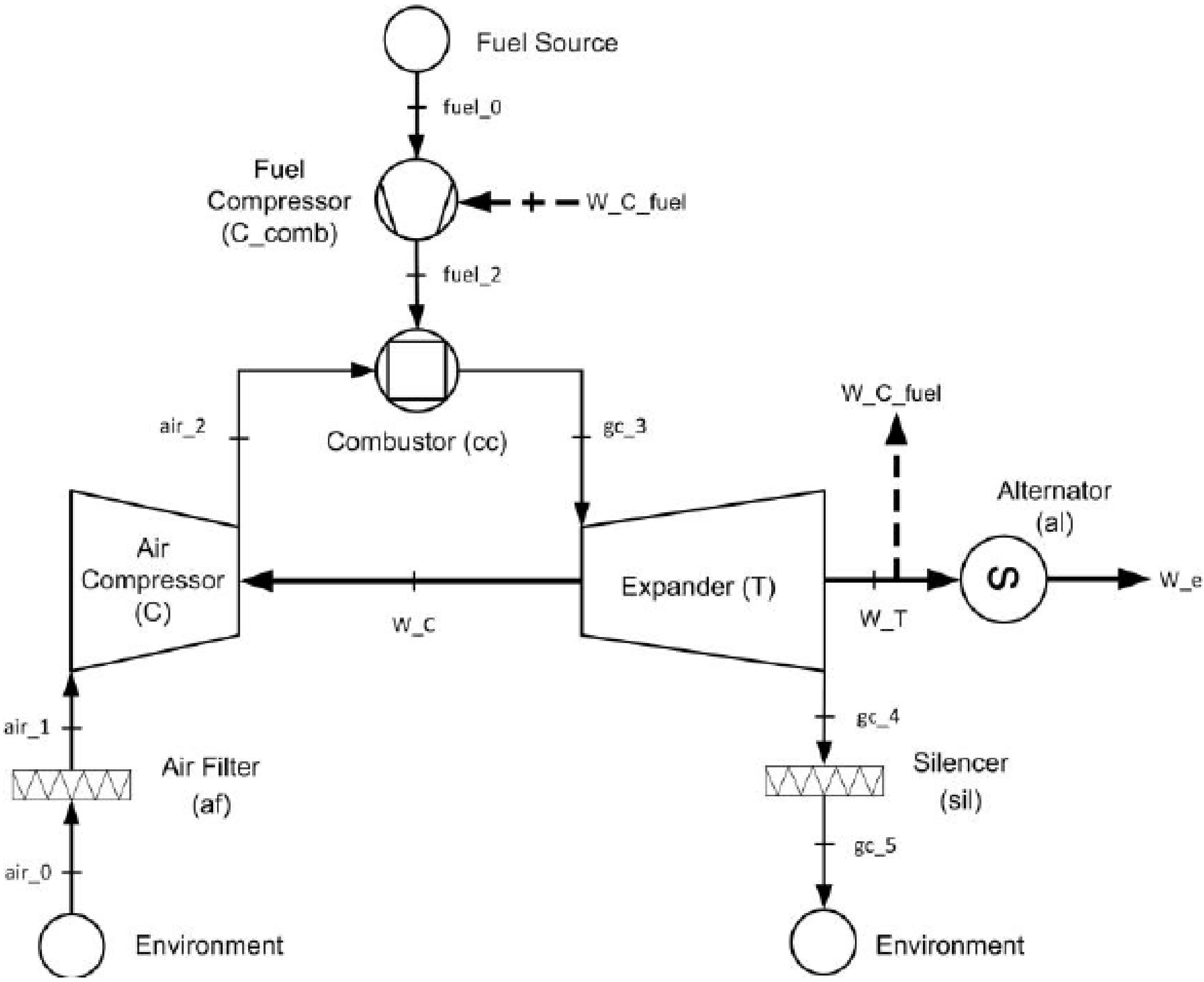



Secondary air
Primary air
Fuel inlet
Flame tube
Tertiary air
Towards gas turbine
Injector
Swirl vanes
Combustion Zone
Mixture and dilution zone


exhaust
air inlet
compressor blades
combustor
fuel in
stator blades
turbine blades
© 1999 Encyclopædia Britannica, Inc.



Schematic arrangement of gas turbine power plant.



3.3.1 Overview

A gas turbine power plant converts fuel energy into electrical energy by using compressed air, combustion, and expansion through a turbine. The major equipment/components each have distinct roles. According to references, the key components include:

- Compressor
- Combustion chamber
- Gas turbine (expander)
- Generator / Alternator
- Supporting/auxiliary systems (fuel system, lubrication, cooling, controls)
  (TutorialsPoint)
  In many modern plants, additional components like regenerators, intercoolers, heat recovery systems (HRSG) may also be present. (Petrotech | Control Systems Solutions)

3.3.2 Major Components & Their Functions

Here's a breakdown of each component, with what it does, what to focus on in design/maintenance, and common issues.

Component	Function	Engineering / Maintenance Notes
Air Intake & Filter	Ambient air enters the plant through intake; filters remove dust/particles.	Dust/sand ingestion can damage compressor blades. Regular filter cleaning/replacement is vital.
Compressor	Draws in ambient air, compresses it to high pressure (increases pressure & temperature) before combustion. (The Department of Energy's Energy.gov)	Multi-stage axial or centrifugal compressor; high mechanical precision required; maintenance issues include blade erosion, fouling, compressor surge/stall. Efficiency of

		compressor has large impact on overall plant efficiency.
Intercooler / Regenerator (optional)	Some designs include heat exchangers/regenerators to recover heat from exhaust or to cool/condition compressed air, improving efficiency. (TutorialsPoint)	Auxiliary systems add complexity; fouling, leaks, thermal stresses must be managed.
Combustion Chamber (Combustor)	Compressed air enters combustor; fuel is injected and combusted; high-temperature, high-pressure gases are generated at (ideally) constant pressure. (acepowerparts.com)	Must withstand very high temperatures (1000-1600 °C); materials, cooling of burner area/turbine inlet critical; emissions (NOx) control is important.
Gas Turbine (Expansion Section)	Hot combustion gases expand through turbine blades; mechanical work produced drives compressor and generator. (The Department of Energy's Energy.gov)	Turbine blades must handle high temperature, high speed, fatigue, corrosion; monitoring for blade erosion/cracks; bearing maintenance is key.
Generator / Alternator	Converts mechanical rotational energy from turbine shaft into electrical energy.	Coupling design, alignment, vibration monitoring, insulation, cooling system (for generator) are maintenance priorities.
Exhaust System	Spent gases leave turbine and are discharged to atmosphere (in simple open cycle) or to a heat recovery system.	Exhaust temperature remains high; opportunity for waste heat recovery (links to Unit III later). Insulation and wear of

		exhaust ducting must be managed.
Auxiliary Systems	Includes fuel supply system, lubrication system, cooling system, control system, starting motor/system. (Fiveable)	These are often overlooked but failures here cause downtime. For example lubrication oil contamination, starting motor failure, fuel injection problems are major maintenance issues.

3.3.3 Special Components for Efficiency / Modernisation

- **Regenerator / Recuperator**: Recovers heat from exhaust and pre-heats incoming compressed air to improve efficiency. Often present in higher-efficiency gas turbines. (TutorialsPoint)
- **Intercooler**: Used between compressor stages when pressure ratio is high; reduces compressor work by cooling intermediate compressed air. (www.slideshare.net)
- **Heat Recovery Steam Generator (HRSG)**: While this is more relevant to combined cycle plants, the gas turbine layout may anticipate exhaust to HRSG for steam production. Component layout must consider this for maintenance and layout design. (EE Power School)

3.3.4 Mechanical/Engineering Perspectives & Maintenance Focus

From a mechanical engineering student/plant-maintenance perspective, here are some **key focus areas**:

- **Material selection & thermal stresses**: Especially in combustor and turbine, materials face high temperature, pressure, and fatigue cycles. Understanding creep, high temperature oxidation, blade cooling is essential.

- **Compressor/turbine aerodynamics**: Blade design, tip clearance, fouling, flow path integrity – small degradations impact performance significantly.
- **Alignment & vibration**: The combustion turbine–compressor–generator assembly is high speed; alignment, rotor balancing, bearing health, lubrication are critical for uptime.
- **Heat loss & efficiency losses**: The components influence the cycle efficiency – e.g., inefficiency in compressor or turbine reduces net output; regenerator/intercooler influences efficiency enhancements.
- **Auxiliary and support systems reliability**: Fuel supply, control systems, starting mechanisms—if these fail, the plant cannot operate regardless of main components.
- **Maintenance scheduling**: Shutdown/inspection of turbine blades, combustor liners, compressor blades; overhaul intervals; check for wear/corrosion/cracks; condition monitoring systems.
- **Environmental & emission considerations**: Combustor design influences NOx formation; exhaust system and layout must consider emission control and heat recovery potential.
- **Integration with cycle improvements**: As you will study in later sections (3.4 etc), component selection & layout influences ability to implement efficiency-improvement methods.

3.3.5 Summary

- Section 3.3 covers the **components of a gas turbine power plant** and their functions: compressor, combustion chamber, gas turbine, generator, and auxiliary systems.
- For each component you need to know what it does, how it's designed/maintained, what common problems arise, and how it affects overall plant performance.
- These components form the backbone of a gas-turbine power plant; their arrangement (as studied in 3.2) and their condition affect efficiency, cost, reliability, and maintenance strategy.
- In your course context: Recognising components helps you in CO3 (gas & waste heat recovery plants), CO2 (maintenance for thermal

plant), and CO5 (economics of component performance, downtime cost).

Methods to Improve Thermal Efficiency of a Simple Open-Cycle Gas Turbine

- **Increasing Pressure Ratio**: Raising the compressor discharge pressure increases the mean temperature at which heat is added, improving efficiency. (Nuclear Power)
- **Raising Turbine Inlet Temperature (TIT)**: Higher TIT means more energy extraction in turbine expansion → higher net work and better efficiency. (LinkedIn)
- **Inter-cooling**: Cooling the air between compressor stages lowers compressor work and improves power output; when combined with regeneration it improves efficiency. (Nuclear Power)
- **Re-heating**: After partial expansion, gases are reheated and undergo further expansion which increases work output; when combined with regeneration it improves cycle performance. (Testbook)
- **Regeneration (Recuperation)**: Using a heat exchanger to transfer heat from turbine exhaust to compressed air so less fuel is needed for same output; improves efficiency especially at lower pressure ratios. (Fiveable)
- **Turbine Inlet Air Cooling (TIAC)**: Lowering the temperature of the intake air increases density, mass flow and reduces compressor work—especially beneficial in hot ambient conditions. (ResearchGate)
- **Combined Methods**: Best results achieved when methods are used together—e.g., inter-cooling + regeneration + re-heating produce significant efficiency gains. (Nuclear Power)

Advantages of Gas Turbine Open Cycle (with efficiency improvement) vs Other Plant Types

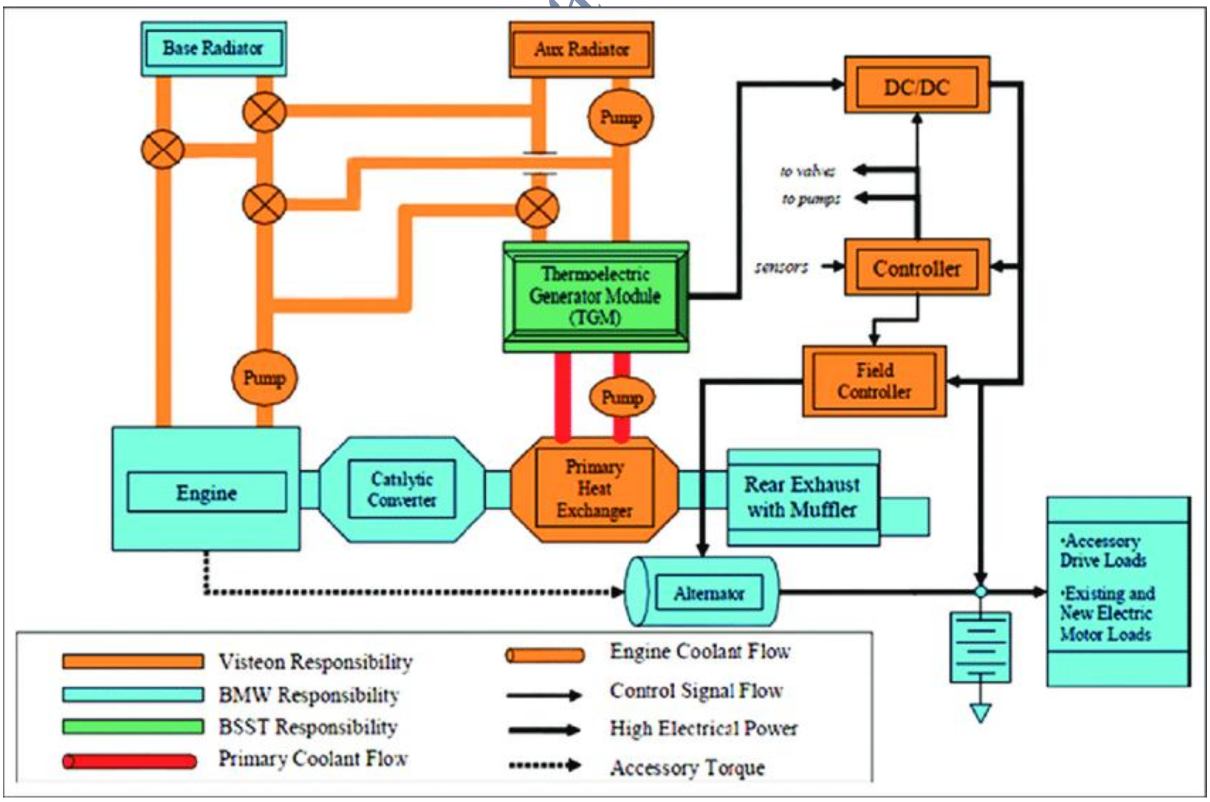
- Faster start-up, less complex auxiliary systems than large steam plants.

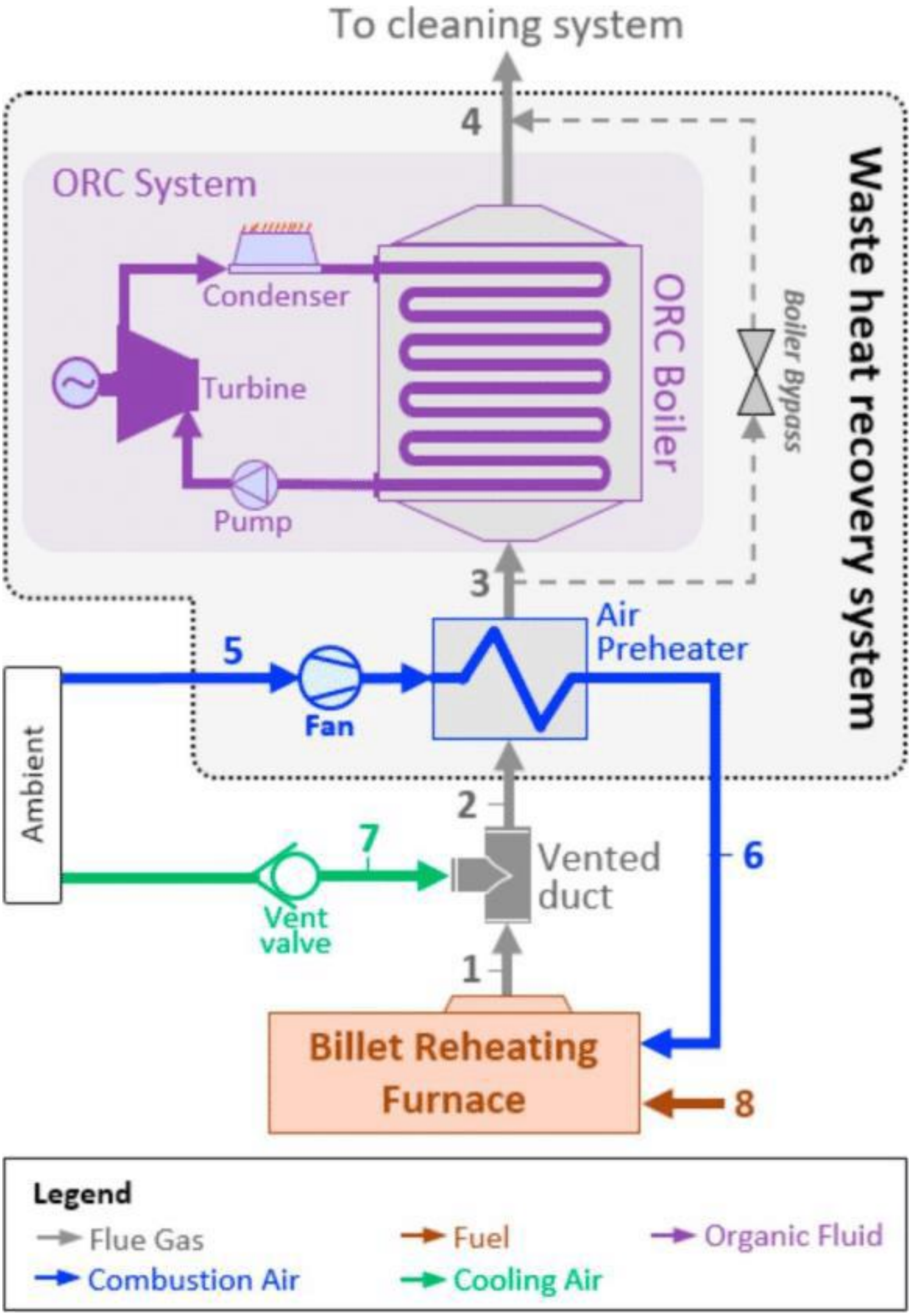
- Smaller footprint, less civil work, less boiler infrastructure.
- More flexible for load changes (peaking, intermediate loads).
- Improved efficiency reduces fuel consumption and emissions (when methods above applied).

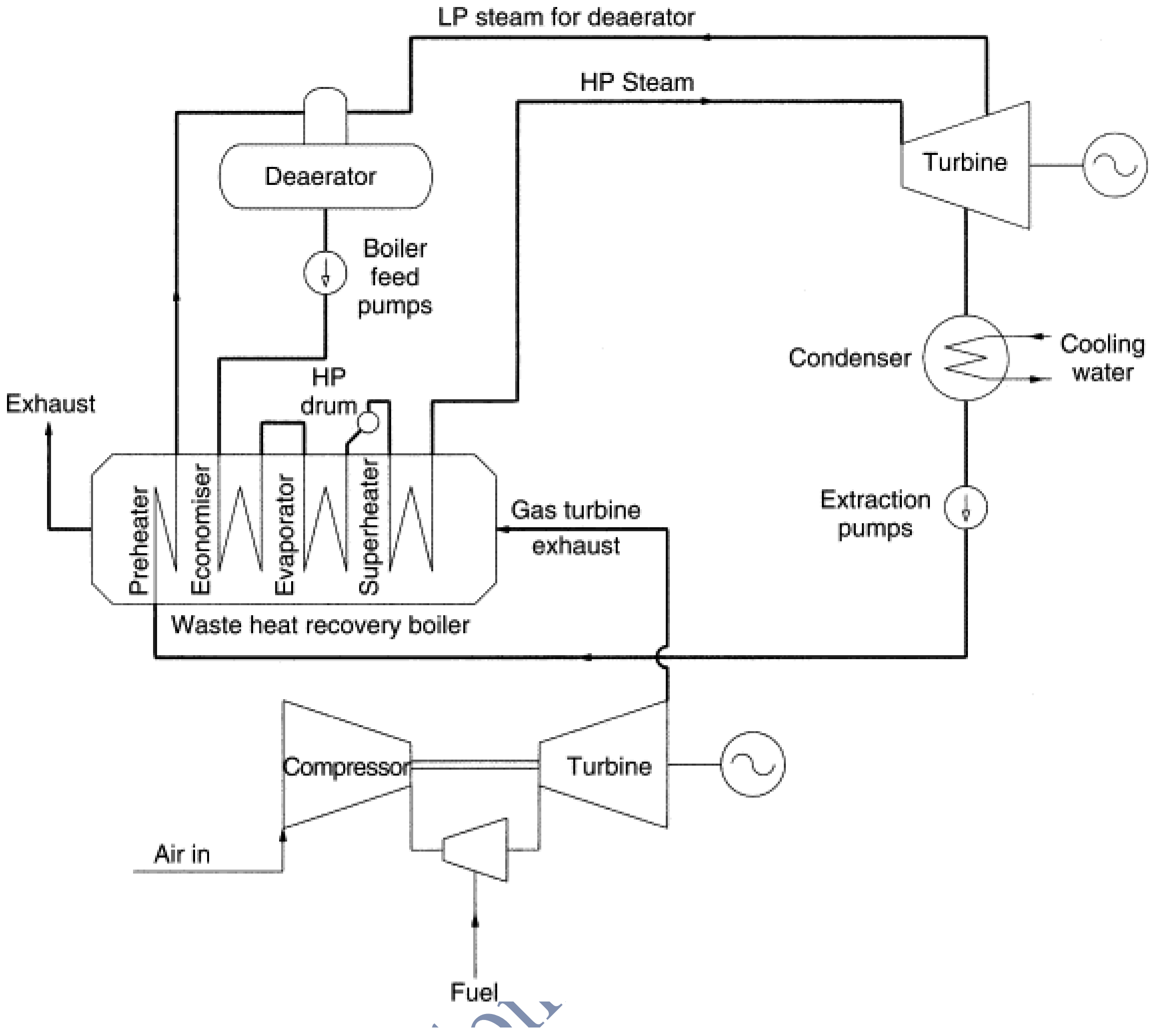
Disadvantages (even with improvement methods)

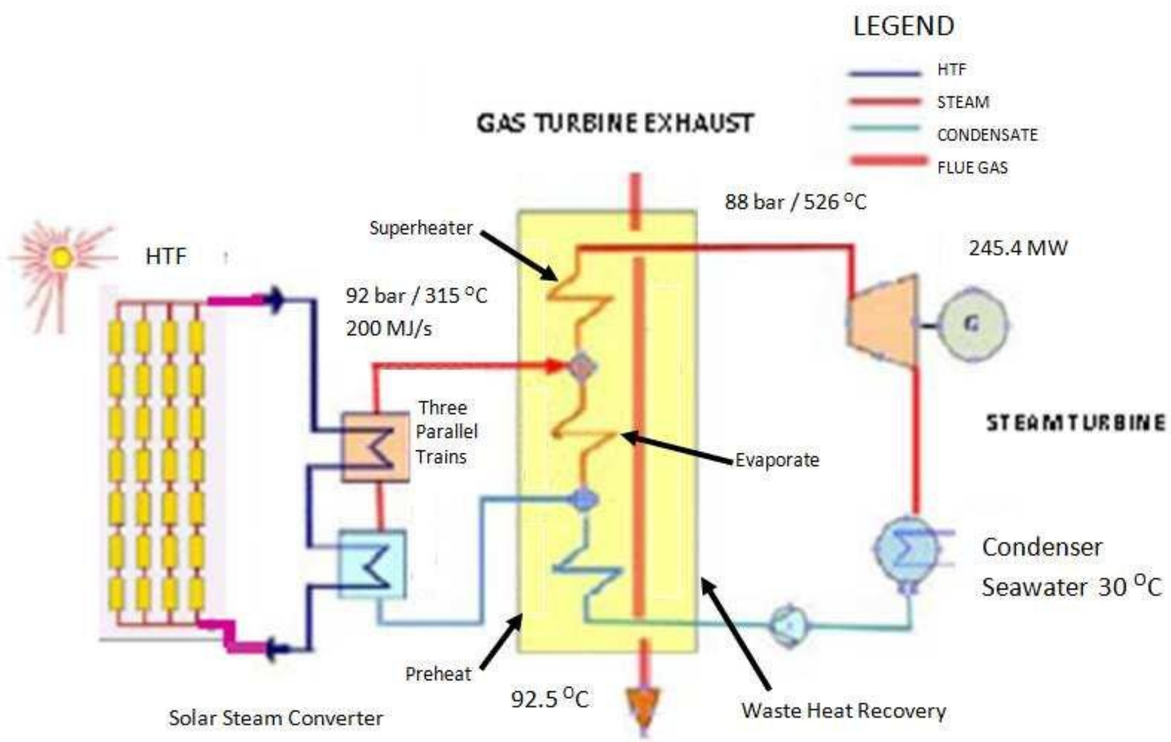
- Even improved simple open-cycle turbines often still have lower efficiency than combined cycle or large steam plants.
- Additional equipment (intercooler, recuperator, reheater) increases capital cost, complexity, maintenance load.
- High TIT and pressure ratio put greater stress on materials, need better cooling, higher maintenance costs.
- Fuel supply must be good quality (gas or clean liquid fuel); for coal or low-quality fuels still less suited.

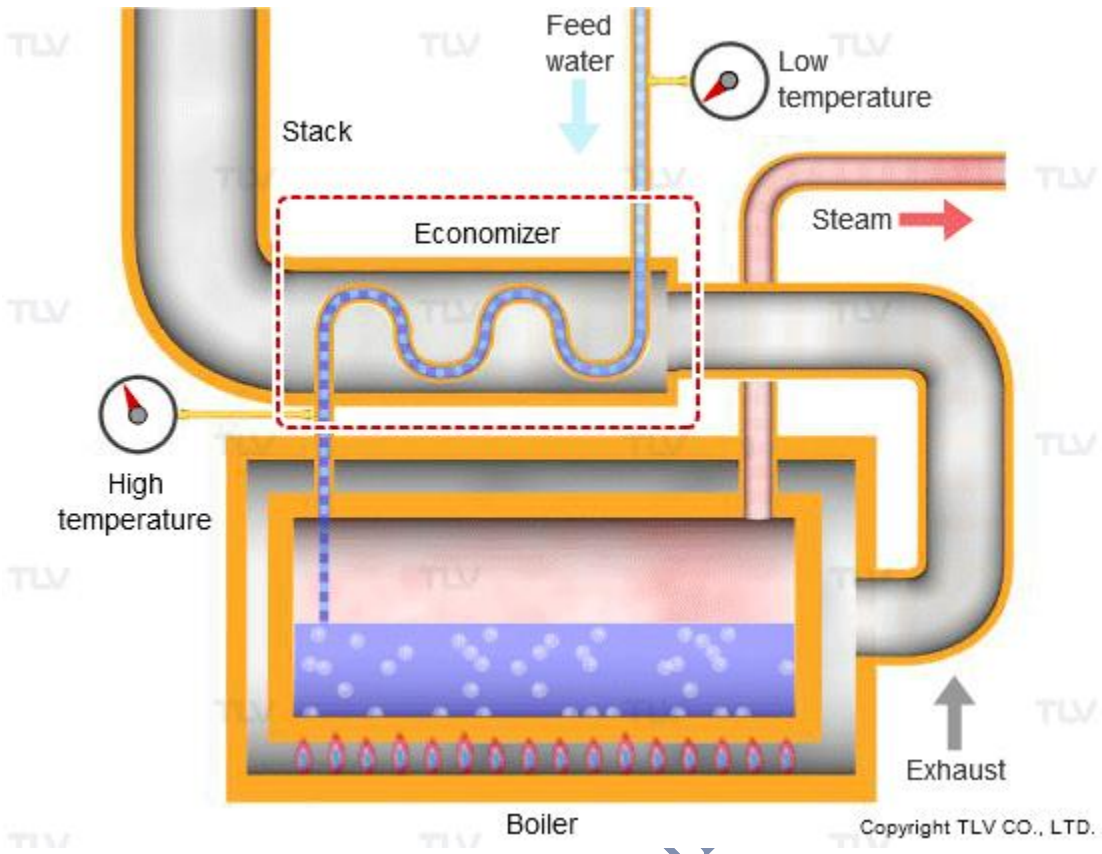
3.5 Waste Heat Recovery in Thermal Power Plants — Need, Opportunities & Present Practices




To cleaning system
4
ORC System
Condenser
Turbine
Pump
ORC Boiler
Boiler Bypass
Waste heat recovery system
3
Air
Preheater
5
Fan
Ambient
2
7
Vented
duct
6
Vent
valve
1
Billet Reheating
Furnace
8
Legend
Flue Gas
Fuel
Organic Fluid
Combustion Air
Cooling Air


LP steam for deaerator
HP Steam
Deaerator
Boiler feed pumps
Turbine
Condenser
Cooling water
Exhaust
HP drum
Preheater
Economiser
Evaporator
Superheater
Gas turbine exhaust
Extraction pumps
Waste heat recovery boiler
Compressor
Turbine
Air in
Fuel


LEGEND
HTF
STEAM
CONDENSATE
FLUE GAS
GAS TURBINE EXHAUST
88 bar / 526 °C
Superheater
HTF
245.4 MW
92 bar / 315 °C
200 MJ/s
Three Parallel Trains
STEAM TURBINE
Evaporate
Condenser
Seawater 30 °C
Preheat
92.5 °C
Solar Steam Converter
Waste Heat Recovery



Definition & Importance

- **Waste heat recovery (WHR)** is the process of capturing and re-using heat energy that would otherwise be lost—for example, hot flue gases, exhaust streams, cooling water discharge—from a power plant or industrial process. (TLV)
- The importance in a power plant context:
  - Improves overall plant thermal efficiency—less fuel wasted.
  - Reduces fuel cost per kWh and lowers emissions (CO_2, NO_x etc) because part of the fuel energy is reused. (BECIS)
  - Reduces thermal pollution (less hot discharge into environment) and aligns with regulations on waste energy utilisation.
  - In modern power systems (especially for CO3 in your syllabus: Gas Power Plant & Waste Heat Recovery) installing WHR is a key strategy for sustainability and economic competitiveness.

📌 Sources & Opportunities in Thermal & Gas Turbine Plants

- Major sources of waste heat in thermal plants:
  - Hot flue gases from boilers, furnaces or gas turbine exhausts (often >300 °C or more). (Thermaxglobal)
  - Cooling water discharge (condensers, once-through cooling) with elevated temperature; this is lower grade but still usable. (Vrcoolertech)
  - Blowdown steam, vent steam, turbine exhausts, ash handling systems—all have heat energy that can be recovered.
- Opportunities for recovering:
  - Use a **Waste Heat Recovery Boiler (WHRB)** or **Heat Recovery Steam Generator (HRSG)** to capture flue/exhaust gas heat and generate steam which can drive a steam turbine or supply process heat. (Thermaxglobal)
  - Pre-heating of feedwater or combustion air using recovered heat to reduce fuel input. (TLV)
  - For lower-temperature waste heat: use Organic Rankine Cycle (ORC) or other bottoming cycles to generate power from moderate temperature levels. (BECIS)
- In your context of power plants, especially gas-turbine or thermal plants, waste heat from the turbine exhaust is a major stream that can be exploited.

🛠 Present Practices & Implementation Examples

- Many industries and power plants already integrate WHR systems: e.g., cement plants installing WHRBs on clinker cooler or pre-heater exhausts to generate steam at 10-30 bar and 300-400 °C superheat for power generation.
- According to industry sources, setting up a WHR power plant (using "free" fuel in the form of wasted heat) improves profitability and reduces carbon footprint. (Thermaxglobal)
- Technologies used range from economisers, recuperators, heat-pipe exchangers, to full WHRB/HRSG units integrated with steam turbines. (Bureau of Energy Efficiency)

- Present practice requires matching waste-heat temperature/flow to an appropriate recovery technology; lower grade (say <150 °C) may not justify large capital cost without good utilisation. (BECIS)

🧑‍🔧 Engineering & Maintenance Implications

- **Design stage**: Identify waste heat streams by temperature, mass flow, composition (e.g., dust in flue gases) and match to recovery technology (WHRB, ORC, economiser).
- **Material selection**: High temperature, corrosive flue gases (especially in coal plants with sulphur) affect heat exchanger materials; fouling and corrosion are key issues.
- **Layout and integration**: Integrating WHR equipment means planning ducting from exhaust, placement of boiler/HRSG, steam turbine or process connection, control systems.
- **Maintenance**: Cleaning of heat-exchanger surfaces, inspection of steam generator tubes, dealing with dust/ash in gases, monitoring of steam quality (if used for turbine), checking of pressure/temperature instrumentation.
- **Economic analysis**: Although fuel is "free", capital cost, maintenance cost, downtime, auxiliary power consumption and life-cycle cost must be accounted. Net benefit = fuel cost saved + possibly revenue from extra power – additional costs.
- **Operation strategy**: In many plants, WHR systems may operate in load following or be endemic to baseload; their performance may drop when waste-heat flow or temperature fluctuates (so controls and integration matter).

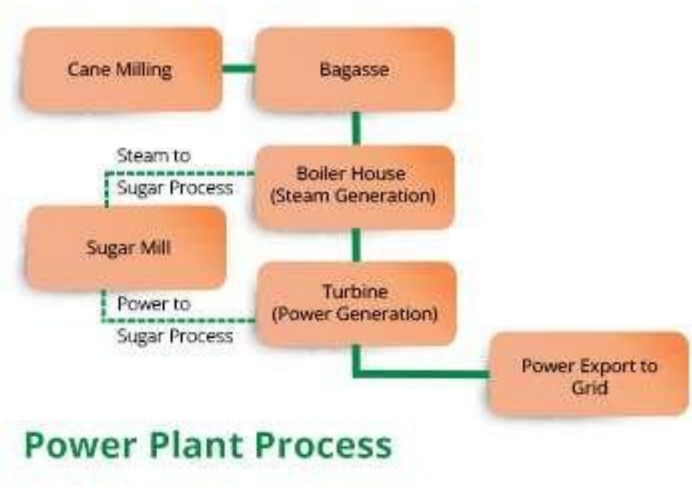
✏️ Exam-Relevant Points (Bullet Style)

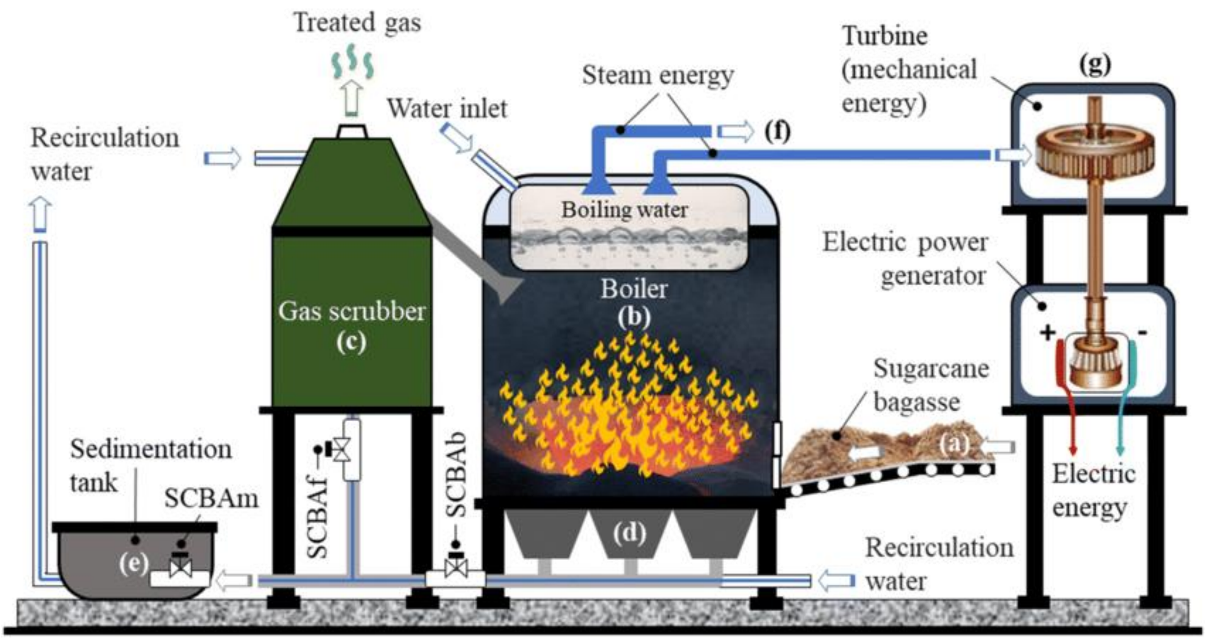
- *Definition*: WHR is reuse of wasted thermal energy from exhausts/fluids which otherwise go to environment.
- *Need*:
  - Raise thermal efficiency of plant.
  - Lower fuel cost and emissions.
  - Reduce environmental heat/thermal pollution.
- *Opportunities*:

- Flue gases (high temp), turbine exhausts, cooling water (lower temp).
- Use WHRB/HRSG, economisers, ORC systems.

- *Present practices*:
    - Many industries/power plants use WHR to generate additional power or supply process heat.
    - Matching temperature levels to correct technology is essential.
- *Key advantages*:
    - "Free" fuel → better economics.
    - Lower emissions → regulatory benefit.
    - Better plant efficiency.
- *Key challenges/disadvantages*:
    - Capital cost of recovery equipment.
    - If waste heat temperature too low, recovery may be uneconomic.
    - Additional maintenance complexity (heat exchangers, fouling) and possible downtime.
    - Availability and consistency of waste-heat stream may vary (especially for plants with variable load) which may reduce effective recovery.
- *Maintenance/engineering focus*: Fouling/corrosion of exchangers, steam quality, integration with existing plant, controls, economics.

Cogeneration (Section 3.6)





✅ Definition & Key Points

- Cogeneration—also called Combined Heat and Power (CHP)—refers to the **simultaneous production** of **electricity (or mechanical power)** *and* **useful thermal energy** (steam, hot water) from the same fuel source. (indiansugar.com)
- In the context of a sugar industry example: the by-product fuel Bagasse (from sugar-cane crushing) is used in a boiler to produce steam that drives a turbine to generate electricity, and the residual steam/heat is used for sugar processing (evaporation, crystallisation). (triveniturbines.com)
- Typical overall efficiencies of cogeneration plants are in the range of **75%-90%**, significantly higher than conventional separate generation (which might be ~35%) because waste heat is utilised. (indiansugar.com)

🎯 Why It's Important & Need

- Many industry plants produce both power and heat needs. By using a single fuel source for both, cogeneration optimises fuel use and reduces waste.

- For sugar mills, using bagasse means they utilise what would otherwise be a waste/by-product, turning it into energy. This reduces dependence on fossil fuel.
- By increasing efficiency and reducing fuel cost and emissions, cogeneration supports economic and environmental goals.
- Also supports your syllabus Outcome CO1 (choosing appropriate fuel) and CO5 (calculating economic parameters) since using bagasse changes fuel cost, availability and economics.

🔍 Opportunities & Application in Sugar Industry

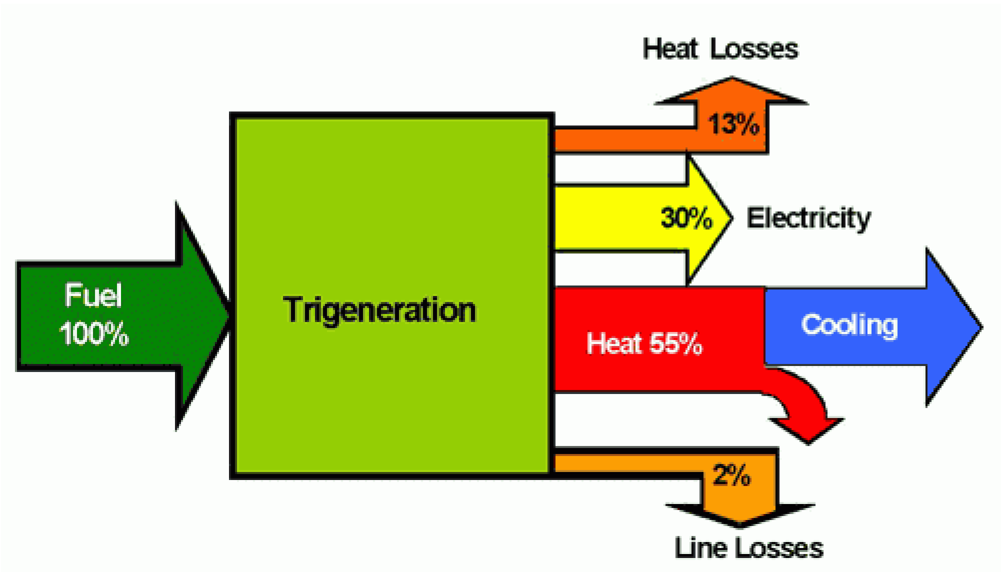
- Fuel source: Bagasse is generated during sugar-cane processing, so the sugar mill has a relatively reliable fuel supply. (i-manager publications)
- Boiler: A bagasse-fired boiler (often of high pressure & temperature) generates steam. The steam drives a turbine/generator to produce electricity. Part of steam is used for sugar processing (heat/steam) and any surplus electricity may be exported to the grid. (triveniturbines.com)
- For example: In India as of December 2024, bagasse-based cogeneration capacity stood at about **9,806 MW**. (REGlobal)
- Economic benefit: The surplus electricity exported adds revenue stream to sugar mills, improving viability. (i-manager publications)

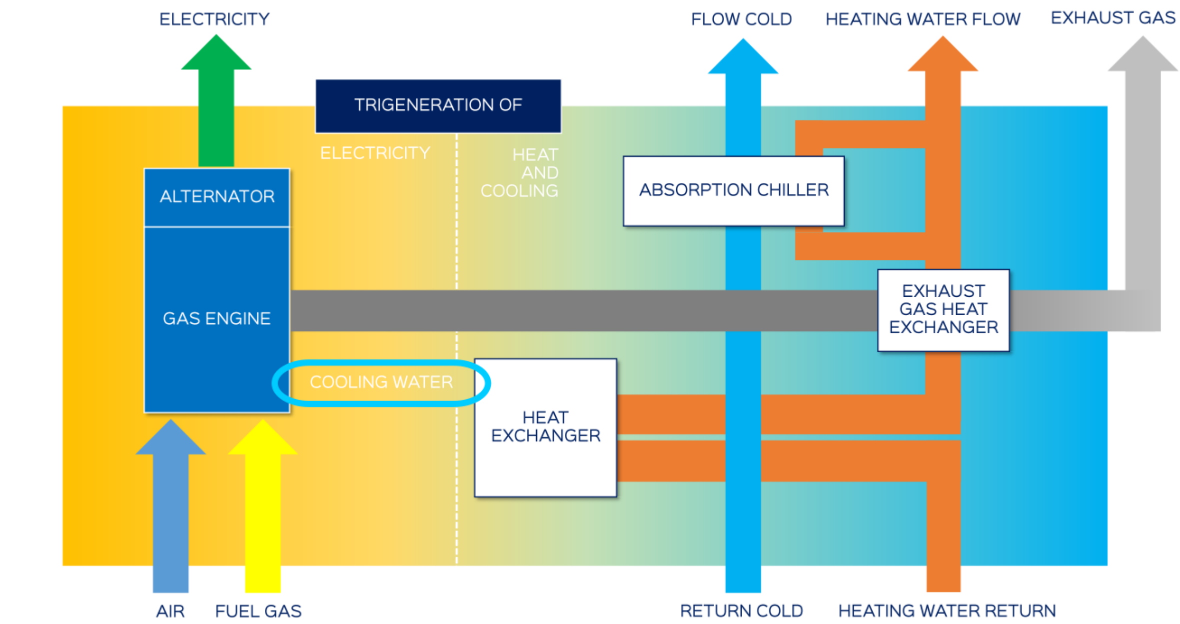
🛠 Engineering / Plant & Maintenance Aspects

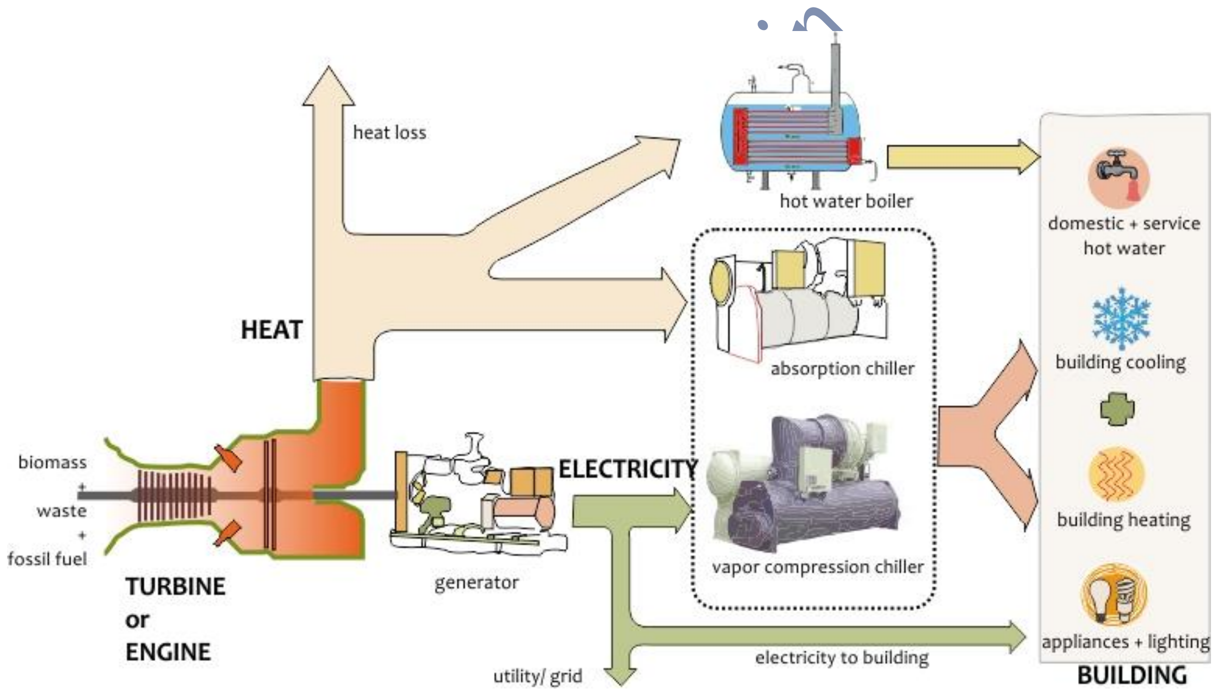
- **Boiler design**: Bagasse has variable moisture and calorific value; the boiler must handle these variations; ash removal systems must cater for biomass ash. (i-manager publications)
- **Steam parameters**: High pressure / high temperature steam improve turbine output. Some sugar industry cogeneration plants target higher pressure and temperature to get more electricity per ton of bagasse. (i-manager publications)
- **Turbine/generator**: Choice between back-pressure turbine, extraction turbine or condensing turbine depending on how much steam is required for process vs electricity. (triveniturbines.com)

- **Integration**: The plant must integrate steam for process and power; control systems must manage both heat and power demands; surplus electricity sales require grid-tie arrangements.
- **Maintenance**: Biomass fuel means potential for slagging, fouling, corrosion; chimneys/exhausts must deal with ash and gases; turbine maintenance considering extraction/bleed lines.
- **Fuel logistics**: Bagasse supply needs management (storage, drying, moisture control) especially off-season; mills may supplement with other biomass/fossil fuel to maintain year-round operation.

3.7 Trigeneration (CCHP — Combined Cooling, Heat & Power)







Here are **exam-friendly detailed notes** on Trigeneration (section 3.7) of Unit III, aligned with your syllabus.

🔍 Definition & Core Concept

- Trigeneration, also known as **CCHP (Combined Cooling, Heat & Power)**, is the simultaneous production of **electricity**, **useful heat**, and **cooling** from a single fuel or energy source. (vitalenergi.co.uk)

- It expands the concept of cogeneration (electricity + heat) by adding cooling as a third useful output, typically by using a heat-driven refrigeration cycle (like an absorption chiller) with the heat output. (Energypedia)

Need & Why It Matters

- Many facilities (large buildings, hospitals, hotels, industrial complexes) have **all three demands**: power, heat (or steam/hot water) and cooling (air-conditioning/cold storage). Trigeneration enables meeting all three from one fuel input rather than separate systems. (EcoMENA)
- Using one integrated system improves overall fuel utilisation efficiency, reduces wastage of heat, and lowers operational cost and emissions compared to separate production of power, heat and cooling. (jenbacher.com)
- From a power-plant engineering viewpoint, trigeneration makes best use of the "waste heat" that would otherwise be lost or under-utilised by converting it into cooling as well. This aligns with your syllabus topic of waste heat recovery and advanced power plant strategies (CO3).

🛠 Key Opportunities & Present Practices

- Typical practice: A prime mover (gas turbine or engine) generates electricity. The waste heat/usable heat output is used for **heating/hot water** and/or is fed into an **absorption chiller** (or refrigeration system) to provide chilled water/cooling. (edina.eu)
- Present application examples:
  - Commercial buildings/ large complexes where cooling load is high and continuous (e.g., shopping malls, hotels) — trigeneration offers value. (EcoMENA)
  - Industrial plants with combined heat & cooling demand and internal power generation — trigeneration helps optimise the fuel input and reduce external purchases.

- Key component: **Absorption/Adsorption Chillers** driven by heat (often from exhaust or hot water) to create cooling rather than electric compression chillers. (jenbacher.com)
- Efficiency: Trigeneration systems can reach very high overall efficiencies (sometimes 70-90%+) because they use fuel for three outputs rather than just one. (EcoMENA)

🎯 Advantages & Considerations

Advantages:

- High overall energy efficiency: More of the fuel input is converted into useful outputs (electricity + heat + cooling) rather than being lost.
- Reduced fuel cost, lower emissions, potential for onsite generation thus less transmission losses.
- Flexibility: The system can serve multiple loads (electricity, heat, cooling) which may vary by season or time of day.
- Good for facilities with major cooling demands and/or simultaneous heat & power loads.

Considerations / Challenges:

- Higher capital cost and complexity compared to simple generation systems: requires integration of generators, heat recovery, absorption chillers, management/control of three output streams.
- Matching of load profiles: To get full benefit, there must be demand for electricity, heat and cooling; if one output is under-utilised, benefits drop.
- Maintenance: More components (heat exchangers, absorption chillers, additional loops) means maintenance management must cover more systems.
- Site suitability: Best when heat and cooling demands co-exist and can use the recovered heat efficiently. If cooling load is low or variable, economics may suffer.

🖇️ Exam-Door Bullet Points

- **Definition**: Trigeneration (CCHP) = electricity + heat + cooling produced simultaneously from single fuel/energy source.
- **Need**: Many facilities have multi-energy demand; separate systems waste fuel; trigeneration improves fuel utilisation and reduces waste.
- **Key Components/Workflow**: Fuel → prime mover (engine or turbine) → electricity; waste heat / usable heat → heat network & absorption chiller → cooling; systems integrated.
- **Applications**: Hotels, hospitals, commercial complexes, industrial plants, data centres with major cooling/heat demand.
- **Advantages**: High overall efficiency, lower fuel cost & emissions, onsite generation, better utilisation of heat.
- **Challenges**: Higher upfront cost, complexity, load matching required, more maintenance.

Diploma Wallah

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