Power Plant Engineering

Lecture 10

Internal Combustion Power Plants

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Lecture learning outcomes:

At the end of this lecture, you will be able to:

i. Explain the fundamental operating principle of a diesel engine, distinguishing the Diesel cycle from the Otto cycle and identifying the key factor of compression ignition.

ii. Describe the main components and energy conversion process in internal combustion engine power plants.

iii. Analyze how supercharging and turbocharging improve engine performance and efficiency.

iv. Identify the layout and functions of major auxiliary systems in diesel power plants.

v. Evaluate different methods used to enhance the efficiency and performance of gas turbine cycles.

Content

1. Principles and Operation of Diesel Engines
2. Internal Combustion Engine Power Plants
3. Supercharging and Turbocharging in Diesel Engines
4. Diesel Engine Power Plant Layout and Auxiliary Systems
5. Modifications and Enhancements of Gas Turbine Cycles

Summary

References

1. Principles and Operation of Diesel Engines

- The core principle that distinguishes a diesel engine from a gasoline engine is Compression Ignition (CI).
- Gasoline Engine (Spark Ignition - SI): A mixture of air and fuel is drawn into the cylinder, compressed, and then ignited by a spark plug.
- The basic principle of a diesel engine is compression ignition.
  - Only air is compressed in the cylinder.
  - The temperature of the air rises due to compression.
  - Fuel is injected at the end of the compression stroke.
  - The fuel self-ignites due to the high temperature.
  - The resulting combustion forces the piston downward, producing mechanical work.

1. Principles and Operation of Diesel Engines Cont…

- Diesel engines are widely used in power plants, heavy vehicles, ships, locomotives, and industrial machinery due to their high efficiency and durability [1].

The Working Cycle: Four-Stroke vs. Two-Stroke

- Four-stroke means the cycle is completed in four distinct piston movements (two up, two down) over two revolutions of the crankshaft.
- Two-stroke means the cycle is completed in just two piston movements (one up, one down) over a single revolution of the crankshaft.
- Two-stroke is a more powerful but less efficient and cleaner cycle.

1. Principles and Operation of Diesel Engines Cont…

- For four-stroke cycle, one power stroke is produced for every two revolutions of the crankshaft.

Stroke	Description	Valve Operation
1. Suction (Intake)	The piston moves downward, drawing fresh air into the cylinder.	Inlet valve open, exhaust valve closed.
2. Compression	The piston moves upward, compressing the air to a high pressure (30–40 bar) and temperature (500–700°C).	Both valves closed.
3. Power (Expansion)	Fuel is injected near the end of the compression stroke. The high temperature of air causes auto-ignition and rapid combustion, forcing the piston down.	Both valves closed.
4. Exhaust	The piston moves upward, expelling burnt gases through the exhaust valve.	Exhaust valve open, inlet valve closed.

1. Principles and Operation of Diesel Engines

Cont…

- Principles of four-stroke diesel cycle

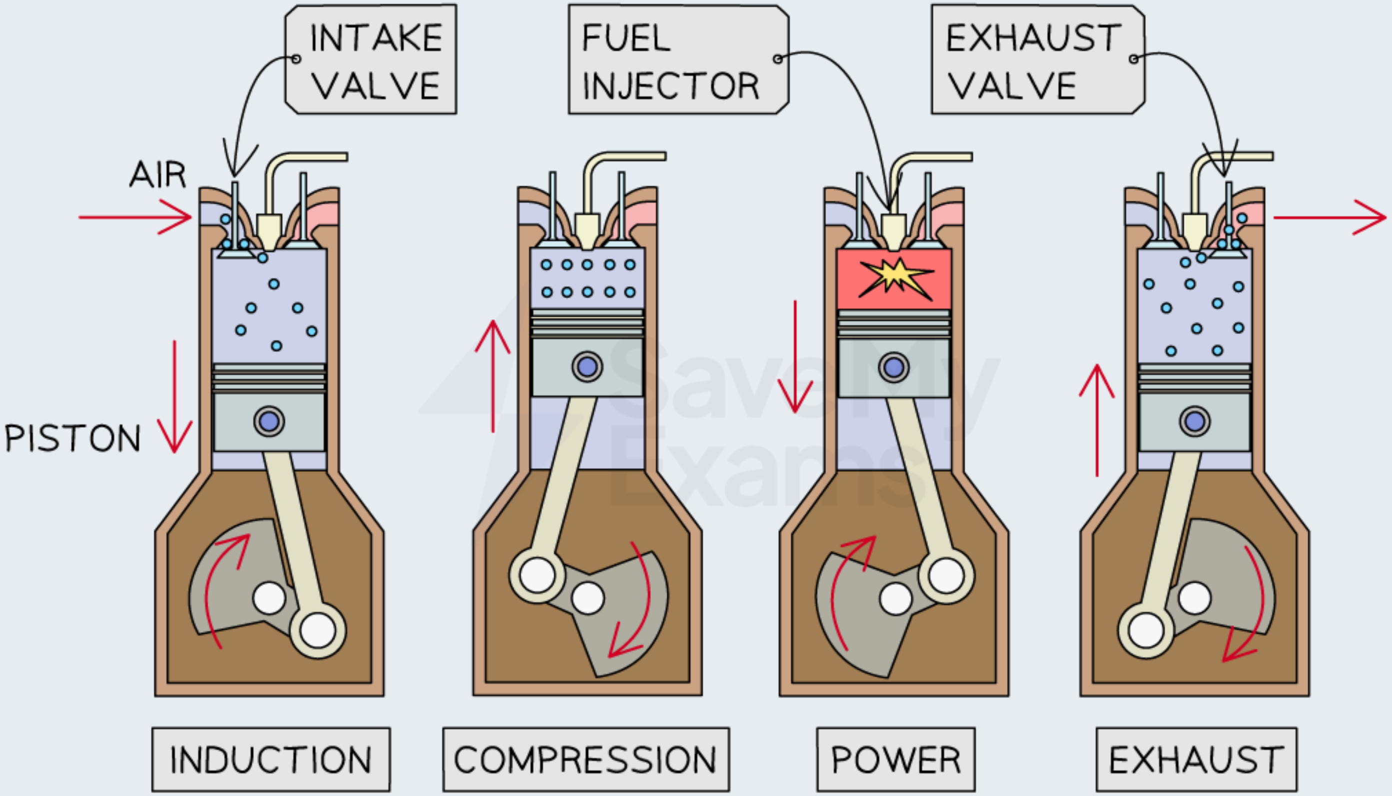

Figure 1: Working principle of Air Standard Diesel Cycle, Engineering Physics: Thermodynamics & Engines — Diesel Engine Cycle, Ashika. (2024)
url: https://cdn.savemyexams.com/uploads/2023/10/11-2-5-diesel-engine.png

1. Principles and Operation of Diesel Engines Cont…

Two-stroke cycle

Stroke	Description
1. Compression and Fuel Injection	The upward stroke compresses air; fuel is injected and ignited. Combustion drives the piston down.
2. Power and Exhaust/Scavenging	As the piston nears bottom dead center, exhaust ports open to expel gases and inlet ports allow fresh air to enter for the next cycle.

- The advantage of two-stroke diesel engine is its simpler design, lighter, and produces power every revolution.
- However, it has lower efficiency and more wear due to higher operating frequency.

1. Principles and Operation of Diesel Engines Cont…

- Principles of four-stroke diesel cycle

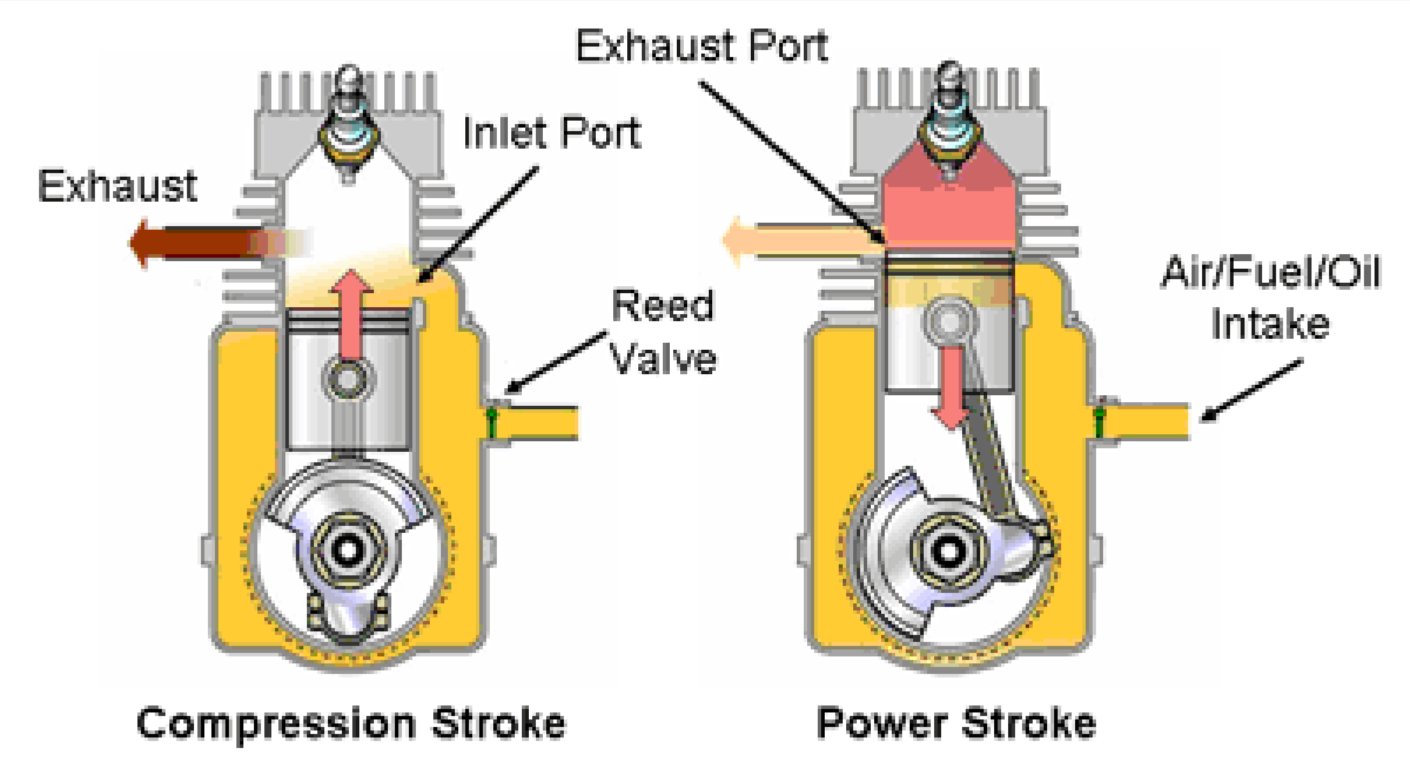

Figure 2: Working Principle of Two Stroke Cycle Diesel Engines, BrainKart, (2016)
url: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRIhYN8bieVYRlJWYp05Ss3phiBRWnpsjnWGw&s

1. Principles and Operation of Diesel Engines Cont…

Fuel Injection and Combustion Process

- This is the heart of the diesel engine's operation and efficiency.
- The objective is to atomize the fuel into a fine mist and distribute it evenly throughout the high-temperature air in the combustion chamber for complete and efficient combustion.

1. Fuel Injection System

- The fuel injection system controls:
  - Timing - when fuel is injected
  - Quantity - how much fuel is injected
  - Atomization - breaking fuel into fine droplets
  - Distribution - even spread of fuel in air

1. Principles and Operation of Diesel Engines Cont…

Combustion Process in Diesel Engines

1. Ignition delay period: Time between the start of injection and start of combustion.
2. Rapid combustion: Accumulated fuel burns rapidly, increasing pressure sharply.
3. Controlled combustion: Injection continues and pressure remains fairly constant.
4. After-burning: Remaining fuel burns as the piston moves downward.

- Efficient combustion depends on:
  - Proper air-fuel mixing
  - Adequate fuel atomization
  - Correct injection timing
  - Proper compression ratio

1. Principles and Operation of Diesel Engines Cont…

Performance Parameters and Efficiency

- Performance parameters provide a quantitative assessment of how efficiently and effectively a diesel engine converts chemical energy in the fuel into useful mechanical work [2].

- Understanding these parameters helps in:
  - ✓Evaluating engine condition and performance.
  - ✓Comparing different engines.
  - ✓Identifying opportunities for improving fuel economy and efficiency.

1. Principles and Operation of Diesel Engines Cont…

Key Performance Parameters

1. Indicated Power (IP) - The total power developed inside the engine cylinder due to combustion of fuel.

$$IP = \frac{P_{mi}\ x\ L\ x\ A\ x\ n\ x\ k}{60}$$

Where: $P_{mi} = indicated\ mean\ effective\ pressure\ (bar)$

$L = stroke\ length\ (m)$

$A = area\ of\ piston\ (m^2)$

$n = number\ of\ power\ strokes\ per\ minute\ per\ cylinder$

$k = number\ of\ cylinders$

$Measured\ by: Indicator\ diagram\ or\ engine\ indicator\ software$

1. Principles and Operation of Diesel Engines Cont…

2. Brake Power (BP)

- The useful power available at the crankshaft output.

$$BP = 2\pi NT/60$$

Where: $N = Engine\ speed\ (rpm)$

$T = torque\ (N.m)$

3. Mean Effective Pressure (MEP)

- The hypothetical constant pressure that, if it acted on the piston during the power stroke, would produce the same work as actually done.

$$MEP = \frac{Work\ done\ per\ cycle}{Swept/displacement\ volume}$$

4. Brake Specific Fuel Consumption (BSFC)

- The rate of fuel consumption per unit power output.

$$BSFC = \frac{\dot{m}_f}{BP}$$

5. Brake Thermal Efficiency (BTE)

- The ratio of brake power to the rate of fuel energy input.

$$\eta_{bth} = \frac{BP}{\dot{m}_f x CV}$$

- $Where$

$$CV = calorific\ value\ of\ fuel\ (kJ/kg)$$

1. Principles and Operation of Diesel Engines Cont…

6. Mechanical Efficiency (η_{m})

- The ratio of brake power to indicated power.

$$\eta_m = \frac{BP}{IP}$$

7. Volumetric Efficiency (η_V)

- A measure of the engine's breathing ability – the ratio of actual air intake to the theoretical air volume.

$$\eta_v = \frac{Actual\ mass\ of\ air\ inducted}{Theoretical\ mass\ of\ air\ that\ could\ fill\ the\ cylinder\ at\ ambient\ conditions}$$

1. Principles and Operation of Diesel Engines Cont…

Factors Affecting Diesel Engine Efficiency

- Design parameters: Compression ratio, combustion chamber shape.
- Operating conditions: Speed, load, and fuel quality.
- Mechanical losses: Friction, pumping, and auxiliary loads.
- Heat losses: Incomplete combustion, exhaust and cooling system losses.
- Supercharging/Turbocharging: Improves volumetric and thermal efficiency.

Methods of Improving Efficiency

- Use of turbochargers and intercoolers.
- Optimized injection timing and fuel atomization.
- Regular maintenance to reduce friction and wear.
- Exhaust heat recovery (e.g., waste heat boilers).
- Advanced materials for reduced heat losses.

2. Internal Combustion Engine Power Plants

- An Internal Combustion Engine Power Plant is an electricity generation facility that uses one or more internal combustion engines as its prime mover [3].
- Unlike external combustion systems (like steam plants), combustion occurs inside the engine cylinder.

Applications:

- Standby and emergency power supply
- Peak load stations
- Remote and isolated power generation
- Marine propulsion and transportation systems

2. Internal Combustion Engine Power Plants Cont…

Principle of Operation

- The working principle of an IC engine power plant is based on the conversion of heat energy from fuel combustion into mechanical work through the expansion of gases in the cylinder [3].

Basic working steps:

1. Air Intake – Air is drawn into the cylinder.
2. Compression – Air is compressed to high pressure and temperature.
3. Combustion (Power Stroke) – Fuel is injected and ignited, producing high-temperature gases.
4. Expansion – The gases expand, pushing the piston and producing mechanical work.
5. Exhaust – Spent gases are expelled from the cylinder.

2. Internal Combustion Engine Power Plants Cont…

Main Components of an IC Engine Power Plant

- A full-scale ICE power plant is more than just an engine. It consists of several critical subsystems:

1. Engine (prime mover):
   - Converts thermal energy to mechanical energy via piston movement.
   - Usually a diesel engine for high efficiency and reliability.
2. Air Intake and Exhaust Systems:
   - Air filter removes dust and impurities.
   - Exhaust silencer reduces noise and releases exhaust gases.

2. Internal Combustion Engine Power Plants Cont…

3. Fuel Supply System:
   - Includes fuel tank, fuel pump, filters, and injectors.
   - Supplies fuel at required pressure and rate for combustion.
4. Cooling System:
   - Removes excess heat to prevent overheating.
   - Uses water or air as coolant.
5. Lubrication System
   - Reduces friction between moving parts and minimizes wear.
   - Includes oil pump, filters, and lubricating oil cooler.

2. Internal Combustion Engine Power Plants Cont…

6. Starting System
   - Starts the engine using electric motors or compressed air.
7. Governing System
   - Controls engine speed and maintains steady power output.
8. Alternator or Generator
   - Converts mechanical energy from the engine into electrical energy.
9. Control and Protection System
   - Monitors operating parameters (temperature, pressure, speed).
   - Includes safety devices for automatic shutdown in case of faults.

2. Internal Combustion Engine Power Plants Cont…

Types of Internal Combustion Engine Power Plants

Type	Description	Typical Use
Diesel Power Plant	Uses compression ignition (CI) engine; most common type.	Standby, base-load, and marine stations
Gas Engine Power Plant	Uses natural gas as fuel with spark ignition.	Cogeneration and small-scale distributed power
Dual-Fuel Engine Power Plant	Operates on both gas and liquid fuel.	Flexible and fuel-efficient operations

2. Internal Combustion Engine Power Plants Cont…

Advantages of IC Engine Power Plants

- Quick starting and easy installation
- High efficiency at part loads
- Lower water requirement (compared to steam plants)
- Compact and portable design
- Suitable for decentralized power generation

Disadvantages

- High running and maintenance costs
- Limited capacity (typically below 50 MW)
- Higher noise and vibration levels
- Shorter life compared to steam or hydro plants
- Fuel supply (especially diesel) may be expensive

3. Supercharging and Turbocharging in Diesel Engines

- Diesel engines are widely used in power generation, transport, and industrial applications due to their high efficiency and durability.
- However, their power output is limited by the amount of air available for combustion.
- To increase the engine's performance, supercharging and turbocharging are used to force more air into the combustion chamber, improving power, efficiency, and overall performance [4].

Why Supercharging and Turbocharging?

- Increase in power output: More air allows more fuel to burn,

  thus increasing the engine's power.
- Improved volumetric efficiency: Forced induction helps fill

  cylinders more effectively.

3. Supercharging and Turbocharging in Diesel Engines Cont…

- **Better combustion:** Sufficient air ensures complete combustion, reducing smoke and unburned fuel.
- **Altitude compensation:** Helps engines maintain power at high altitudes where air density is lower.
- **Reduction in engine size:** Higher power from smaller engines results in weight and space savings.

Supercharging

- Supercharging is the process of increasing the pressure of the intake air above atmospheric pressure using a mechanically driven compressor connected to the engine crankshaft.

3. Supercharging and Turbocharging in Diesel Engines Cont…

Types of Superchargers

1. Roots Supercharger

- Uses two meshing lobes to pump air.
- Provides high boost at low speeds.
- Common in racing and heavy-duty applications.

2. Centrifugal Supercharger

- Uses an impeller to accelerate air outward.
- Compact, efficient at high engine speeds.

3. Twin-Screw Supercharger

- Uses intermeshing helical rotors.
- Provides smoother and efficient compression than Roots type.

3. Supercharging and Turbocharging in Diesel Engines Cont…

Turbocharging

- Turbocharging uses a turbine driven by exhaust gases to power a compressor that forces air into the engine cylinders.
- It recovers energy from the exhaust that would otherwise be wasted.

Types of Turbochargers

1. Single Turbo: Simple and compact.
2. Twin Turbo: Two turbos—one small and one large—to cover a wide speed range.
3. Variable Geometry Turbo (VGT): Adjustable vanes optimize boost pressure at all speeds.
4. Sequential Turbocharging: Smaller turbo operates at low speed, larger one at high speed.

4. Diesel Engine Power Plant Layout and Auxiliary Systems

- A typical diesel power plant consists of main and auxiliary components systematically arranged to ensure smooth operation, efficient power generation, and ease of maintenance.

The following are major and auxiliary units in the layout:

1. Air Intake System
    - Supplies clean, filtered air for combustion.
    - Includes air filters, turbochargers or superchargers, and intake manifolds.
    - Air may be cooled by intercoolers after compression to improve density and combustion efficiency.

4. Diesel Engine Power Plant Layout and Auxiliary Systems Cont…

2. Fuel Supply System

- Stores and delivers fuel at the required pressure and quantity.
- Major components:
  - ✓Fuel storage tanks (main and day tanks)
  - ✓Fuel transfer pump
  - ✓Fuel filter and strainers
  - ✓Fuel injection pump and injectors

3. Cooling System

- Removes excess heat from the engine to maintain optimal operating temperature.
- The types of cooling system are air cooling (for small engines) and water cooling (for medium and large engines).

4. Diesel Engine Power Plant Layout and Auxiliary Systems Cont…

- Components of cooling system:
  - ✓Radiator or heat exchanger
  - ✓Coolant pump
  - ✓Cooling tower (in large plants)
  - ✓Thermostat and expansion tank

4. Lubrication System

- Reduces friction between moving parts, prevents wear, and removes heat.
- Components of a lubrication system:
  - ✓Oil pump
  - ✓Oil filter
  - ✓Oil cooler
  - ✓Oil sump or reservoir
- Lubrication methods: Splash system, pressure system, or combination.

5. Exhaust System

- Expels combustion gases safely and reduces noise and emissions.
- Components:
  - Exhaust manifold
  - Silencer or muffler
  - Exhaust gas heat recovery system (optional) for heating or turbocharging.

6. Starting System

- Provides the initial rotation for the engine crankshaft.
- The methods of a starting system are:
  - Electric starter motor (battery operated)
  - Compressed air starting system (for large engines)

4. Diesel Engine Power Plant Layout and Auxiliary Systems Cont…

7. Governing and Control System

- Maintains constant engine speed and load sharing.
- Includes:
  - ✓Speed governor
  - ✓Load controller
  - ✓Automatic voltage regulator (AVR) for generator output control.

8. Generator (Alternator)

- Converts mechanical energy into electrical energy.
- Typically a synchronous alternator directly coupled to the diesel engine.

4. Diesel Engine Power Plant Layout and Auxiliary Systems Cont…

9. Switchgear and Control Panel

- Manages power distribution and protection.
- Includes:
  - ✓Circuit breakers
  - ✓Meters and indicators
  - ✓Control relays and protection devices

10. Exhaust Gas Treatment and Emission Control (in modern plants)

- Systems such as diesel particulate filters (DPF), selective catalytic reduction (SCR), and oxidation catalysts are added for emission compliance.

4. Diesel Engine Power Plant Layout and Auxiliary Systems

Diesel Power Plant Layout and Systems

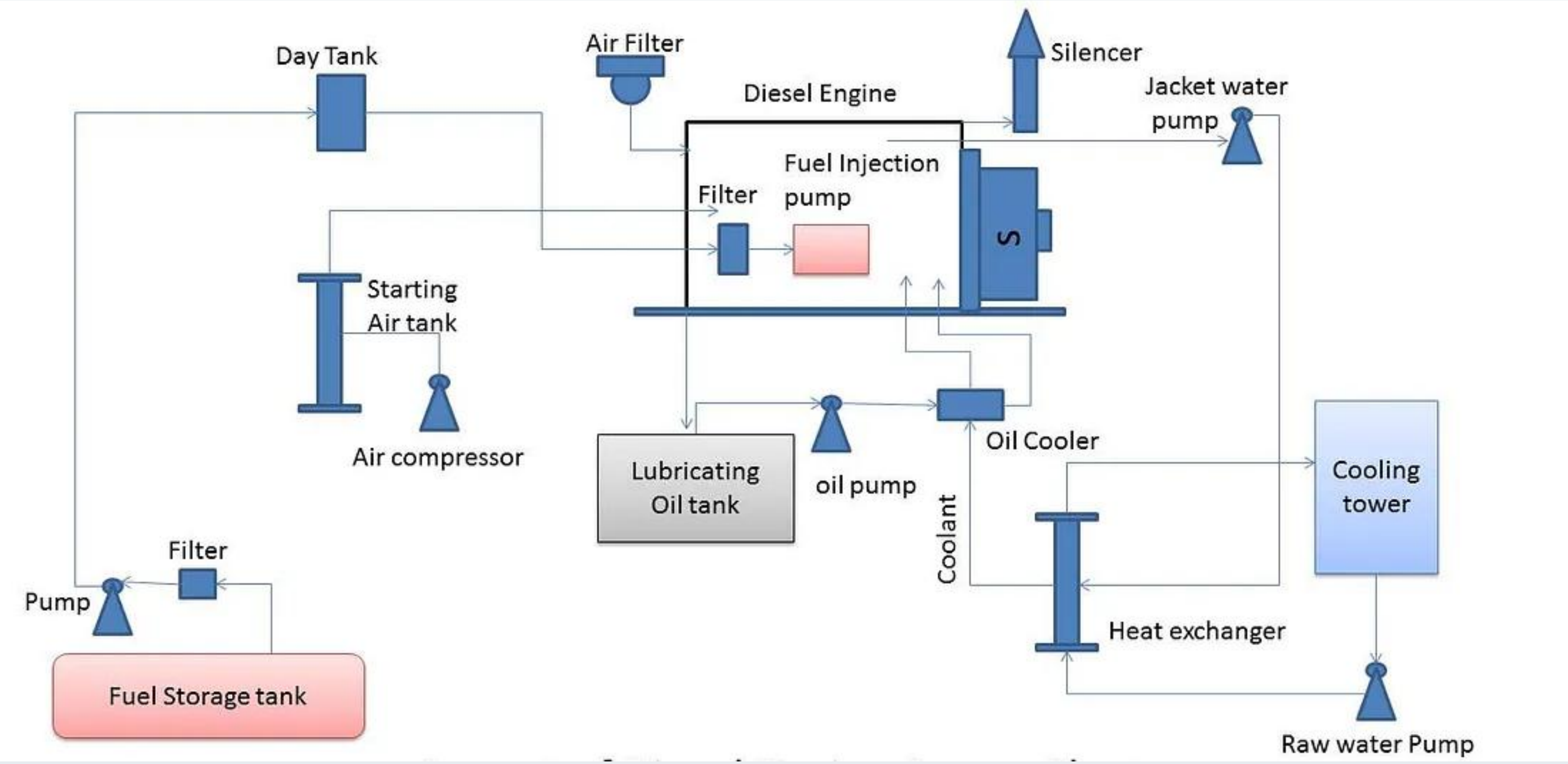

Figure 3: Layout of Diesel Power Plant. Soetrisno, Y. A. A., Winardi, B. W., & Sinuraya, E. W. (2022). url:https://miro.medium.com/v2/resize:fit:1100/format:webp/1*EZpwm1IYAarjqlEeDplk0g.jpeg

5. Modifications and Enhancements of Gas Turbine Cycles

- Gas turbines are widely used in power generation because of their compactness, high power-to-weight ratio, and rapid start-up [5].
- However, their efficiency is limited by the simple Brayton cycle's temperature and pressure constraints.
- It has fundamental limitations in practical power generation:
  - ✓ High specific fuel consumption: Lower thermal efficiency compared to advanced steam plants at low pressure ratios.
  - ✓ Significant power drop with temperature: Output and efficiency are highly sensitive to ambient air temperature.
  - ✓ Poor part-load efficiency: Performance degrades rapidly when operating below the design capacity.

5. Modifications and Enhancements of Gas Turbine Cycles **Cont…**

- To improve performance, several modifications and enhancements are applied to the basic gas turbine cycle, aiming to increase thermal efficiency, power output, or both.
- The primary goal of modifications is to increase the net work output and the thermal efficiency of the cycle.

  This is achieved by:

  ✓Increasing the average temperature of heat addition.

  ✓Decreasing the average temperature of heat rejection.

  ✓Utilizing the exhaust gas energy, which is otherwise wasted.

5. Modifications and Enhancements of Gas Turbine Cycles Cont…

- Key Modifications & Enhancements of Gas Turbine Cycles

1. Intercooling

▪ Compressing air in multiple stages with cooling between stages reduces compressor work.

▪ Intercooling decreases compressor work input, increases net work output, but slightly reduces thermal efficiency unless combined with regeneration.

2. Reheating

▪ Expanding air in multiple turbine stages with reheating between stages increases turbine work and specific power output.

5. Modifications and Enhancements of Gas Turbine Cycles Cont…

3. Regeneration (Recuperation)

- Heat from the hot exhaust gases is used to preheat compressed air before combustion.
- A heat exchanger (regenerator or recuperator) transfers heat from turbine exhaust to compressor outlet air.
- It reduces fuel consumption (less heat required in the combustor) and increases thermal efficiency, especially at low pressure ratios.

5. Modifications and Enhancements of Gas Turbine Cycles Cont…

4. Combined Cycle

- Waste heat from the gas turbine exhaust is used to generate steam for a steam turbine (Rankine cycle).
- The arrangement is:

  Gas turbine → Heat Recovery Steam Generator (HRSG) → Steam turbine → Generator.
- Increases overall plant efficiency, efficient utilization of exhaust heat but higher capital cost and complexity.

5. Modifications and Enhancements of Gas Turbine Cycles Cont…

5. Cogeneration (Combined Heat and Power)

- Exhaust heat is used directly for industrial heating, process steam, or district heating rather than generating additional power.
- It increases overall energy utilization efficiency and reduces fuel cost and environmental impact.

6. Advanced Enhancements

a. Intercooled–Regenerative–Reheat Cycle (IRR Cycle)

- Combines intercooling, reheating, and regeneration.
- Provides high efficiency and power but complex and costly.

5. Modifications and Enhancements of Gas Turbine Cycles Cont…

b. Water or Steam Injection

- Injects water/steam into the combustor or compressor to increase mass flow and reduce NOx emissions.
- Enhances power output but reduces turbine life.

c. Chemical Recuperation

- Uses exhaust heat for endothermic reactions (e.g., steam reforming of methane).
- Increases efficiency and produces hydrogen-rich fuel.

Summary

- Diesel engines operate on the compression ignition principle, converting chemical energy of fuel into mechanical work through four or two-stroke cycles.
- Internal combustion engine power plants use diesel or gas engines to produce electricity efficiently, suitable for small to medium-scale and standby power generation.
- Supercharging and turbocharging in diesel engines increases the air pressure using compressors or exhaust-driven turbines to enhance power output, efficiency, and fuel economy.
- Diesel engine power plant layout and auxiliary systems includes main engine, air intake, exhaust, fuel, cooling, and lubrication systems arranged for smooth, safe, and efficient operation.
- Modifications and enhancements of gas turbine cycles includes techniques like intercooling, reheating, and regeneration to improve thermal efficiency, power output, and fuel utilization in gas turbine systems.

References

[1]. Diesel engines: Technologies, operation, and industrial applications, Inspenet.com, 2023.

[2]. Performance, Design and Operational Parameters of Variable Compression Ratio Diesel Engine. Khanyi, N. F., & Inambao, F. (2024). The Journal of Propulsion Technology & Power Technology.

[3]. Review of efficiencies of cogeneration units using internal combustion engines. Vukašinović, V., Gordić, D., Babić, M., Jelić, D., & Končalović, D. (2016). International Journal of Green Energy, 13(5), 446-453.

[4]. Diesel engine fuel economy improvement enabled by supercharging and down-speeding. Keidel, S., Wetzel, P., Biller, B., Bevan, K., & Birckett, A. (2012). SAE International Journal of Commercial Vehicles, 5(2).

[5]. Saravanamuttoo, H. I. H., et al. (2017). Gas Turbine Theory (7th ed.). Pearson. (Covers fundamental principles applicable to steam turbines).

Thank you !