Thermal Engineering-II

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- Thermal Engineering-II primarily focuses on applied thermodynamics.
- Key areas include Internal Combustion (IC) Engines, Refrigeration, Air-Conditioning, and Hydrogen Technology.
- Understanding IC engines is crucial for the automotive and power generation sectors.
- The goal is to maximize efficiency while minimizing emissions.

Definition

A heat engine is a device that transforms the chemical energy of a fuel into thermal energy and uses this energy to produce useful mechanical work.

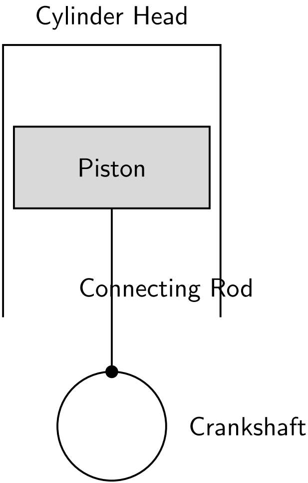
Classification of Heat Engines:

- External Combustion (EC) Engines
- Internal Combustion (IC) Engines

External Combustion	Internal Combustion
Combustion outside cylinder	Combustion inside cylinder
Working fluid is usually steam	Working fluid is a mixture of air and fuel
Requires boiler and condenser	Compact design
Examples: Steam engine, steam turbine	Examples: Petrol engine, diesel engine

Table: Comparison of EC and IC Engines

- **According to Type of Fuel Used:** Petrol, Diesel, Gas engines.
- **According to Method of Ignition:** Spark Ignition (SI), Compression Ignition (CI).
- **According to Number of Strokes:** Two-stroke, Four-stroke.
- **According to Cycle of Operation:** Otto cycle, Diesel cycle, Dual cycle.
- **According to Cooling System:** Air-cooled, Water-cooled.


Cylinder Head
Piston
Connecting Rod
Crankshaft

- **Cylinder:** The main part where combustion takes place.
- **Piston:** A cylindrical component that moves back and forth in the cylinder.
- **Piston Rings:** Provide a seal between piston and cylinder wall.
- **Connecting Rod:** Connects the piston to the crankshaft.
- **Crankshaft:** Converts reciprocating motion into rotary motion.
- **Valves:** Control the flow of fresh charge and exhaust gases.

1. **Suction (Intake) Stroke:** Air-fuel mixture (SI) or just air (CI) is drawn into the cylinder.
2. **Compression Stroke:** The charge is compressed by the upward moving piston.
3. **Expansion (Power) Stroke:** Combustion occurs, high pressure pushes the piston down.
4. **Exhaust Stroke:** Burned gases are expelled from the cylinder.

Two-Stroke Engine	Four-Stroke Engine
One power stroke per crank revolution	One power stroke per two crank revolutions
Lighter and more compact	Heavier and bulkier
Uses ports instead of valves	Uses inlet and exhaust valves
Lower thermal efficiency	Higher thermal efficiency

Table: Comparison of Two-Stroke and Four-Stroke Engines

- Runs on the Otto cycle (constant volume heat addition).
- Uses a carburetor or fuel injector to mix air and petrol before it enters the cylinder.
- Requires a spark plug to ignite the mixture.
- Generally operates at lower compression ratios (typically 8:1 to 12:1).
- Used in motorcycles, passenger cars, and light vehicles.

- Runs on the Diesel cycle (constant pressure heat addition).
- Only air is inducted during the suction stroke.
- Fuel is injected directly into the cylinder at the end of compression.
- Ignition occurs due to the high temperature of the compressed air (auto-ignition).
- Operates at higher compression ratios (typically 14:1 to 24:1).
- Used in heavy vehicles, ships, and power plants.

Several key parameters define the performance of an IC engine:

- **Indicated Power (IP):** Power developed inside the cylinder.
- **Brake Power (BP):** Actual power available at the crankshaft.
- **Friction Power (FP):** Power lost due to friction (IP = BP + FP).
- **Mechanical Efficiency:** $\eta_m = \frac{BP}{IP}$
- **Thermal Efficiency:** $\eta_{th} = \frac{\text{Power}}{\text{Heat supplied}}$

Summary

IC engines are fundamental power units converting chemical energy to mechanical work. They are classified primarily by fuel type (SI/CI) and operating cycle (2-stroke/4-stroke).

Key Applications:

- Automotive industry (cars, trucks, motorcycles)
- Marine propulsion
- Aviation (piston-engine aircraft)
- Portable power generators and lawnmowers

- In four-stroke engines, valves control the entry of fresh charge and exit of exhaust gases.
- Valve timing refers to the exact opening and closing points of these valves relative to the piston position (crank angle).
- Proper timing is crucial for maximizing volumetric efficiency and power output.
- We study two types of diagrams: Theoretical and Actual.

- **TDC (Top Dead Center):** The highest position of the piston in the cylinder.
- **BDC (Bottom Dead Center):** The lowest position of the piston.
- **IVO (Inlet Valve Opens):** Point where the inlet valve begins to open.
- **IVC (Inlet Valve Closes):** Point where the inlet valve fully closes.
- **EVO (Exhaust Valve Opens):** Point where the exhaust valve begins to open.
- **EVC (Exhaust Valve Closes):** Point where the exhaust valve fully closes.

In a theoretical (ideal) engine, valve events occur exactly at the dead centers:

- **Suction:** IVO at TDC, IVC at BDC. Duration $= 180^\circ$.
- **Compression:** Both valves closed. BDC to TDC. Duration $= 180^\circ$.
- **Expansion:** Both valves closed. TDC to BDC. Duration $= 180^\circ$.
- **Exhaust:** EVO at BDC, EVC at TDC. Duration $= 180^\circ$.

Note: This assumes instantaneous opening and closing of valves.

Why Theoretical Timing Fails in Practice

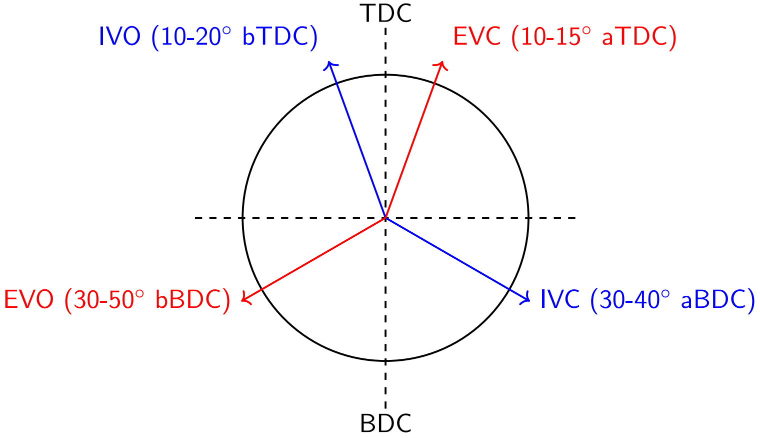
Valves have inertia and require time to open and close. If an inlet valve starts opening exactly at TDC, it won't be fully open when the piston begins moving down, restricting airflow.

Practical constraints:

- Mechanical lag in cams, pushrods, and springs.
- Inertia of the gas column (ram effect).
- Need for adequate scavenging of exhaust gases.

To overcome mechanical and fluid dynamic limitations, actual timings are modified:

- **Valve Lead:** Opening a valve before the theoretical dead center.
- **Valve Lag:** Closing a valve after the theoretical dead center.
- **Valve Overlap:** The period during which both inlet and exhaust valves are open simultaneously.


TDC
IVO (10-20° bTDC)
EVC (10-15° aTDC)
EVO (30-50° bBDC)
IVC (30-40° aBDC)
BDC

- **Inlet Valve Lead (10-20° before TDC):** Ensures the valve is sufficiently open by the time the piston starts moving down, allowing maximum fresh charge to enter.
- **Inlet Valve Lag (30-40° after BDC):** Takes advantage of the inertia of the incoming fast-moving charge. The charge continues to enter the cylinder even as the piston starts moving up, increasing volumetric efficiency (Ram effect).

- **Exhaust Valve Lead (30-50° before BDC):** Releases the blow-down pressure early, reducing the work the piston must do to push out the gases during the exhaust stroke.
- **Exhaust Valve Lag (10-15° after TDC):** Uses the momentum of the outgoing exhaust gases to help pull in the fresh charge (scavenging effect).

Definition

Valve overlap is the period when both the inlet and exhaust valves are open simultaneously. It occurs near TDC.

Purpose:

- Helps in better scavenging (clearing out exhaust gases).
- Uses the vacuum created by exiting exhaust gases to draw in the fresh mixture.
- Overlap period = (IVO advance) + (EVC retard).

The diagram for a CI (Diesel) engine is similar to the SI engine, but with slight variations and the addition of fuel injection timing.

- **IVO:** 10-25° before TDC
- **IVC:** 25-50° after BDC
- **EVO:** 30-50° before BDC
- **EVC:** 10-15° after TDC
- **FIO (Fuel Injection Opens):** 5-10° before TDC
- **FIC (Fuel Injection Closes):** 15-20° after TDC

Event	**SI Engine**	**CI Engine**
IVO (bTDC)	10° - 20°	10° - 25°
IVC (aBDC)	30° - 40°	25° - 50°
EVO (bBDC)	30° - 50°	30° - 50°
EVC (aTDC)	10° - 15°	10° - 15°
Ignition/Injection	Spark bTDC	Injection bTDC

Table: Typical Valve Timing Values

Two-stroke engines use ports (uncovered by the piston) instead of valves.

- Events are symmetrical around the dead centers because the piston controls the opening and closing.
- **Transfer Port:** Opens $\sim 40 - 50^{\circ}$ before BDC, closes $\sim 40 - 50^{\circ}$ after BDC.
- **Exhaust Port:** Opens $\sim 60 - 70^{\circ}$ before BDC, closes $\sim 60 - 70^{\circ}$ after BDC.
- The exhaust port opens before the transfer port (blow-down period) to reduce cylinder pressure before the fresh charge enters.

- In traditional SI engines, fuel and air are mixed in a carburetor.
- Modern engines (both SI and CI) utilize Fuel Injection Systems for precise control over the air-fuel mixture.
- **Primary Purpose:** To deliver accurately metered and finely atomized fuel into the engine cylinder at the exact correct moment.
- Crucial for meeting emission standards, improving fuel economy, and maximizing power output.

A well-designed fuel injection system must perform the following tasks:

1. **Metering:** Measure the exact quantity of fuel required for the engine load and speed.
2. **Timing:** Inject the fuel at the precise crank angle.
3. **Atomization:** Break the liquid fuel into tiny droplets for rapid vaporization.
4. **Distribution:** Ensure uniform distribution of fuel throughout the combustion chamber.
5. **Pressurization:** Provide sufficient pressure to force the fuel into the highly compressed air (especially in CI engines).

In Compression Ignition (Diesel) engines, fuel injection systems are broadly classified into:

- **Air Injection System:**
  - Uses compressed air to atomize and inject fuel.
  - Obsolete due to the bulkiness of the multi-stage air compressor.
- **Solid (Airless) Injection System:**
  - Fuel is pressurized by a mechanical pump and injected directly.
  - Universally used in modern diesel engines.

Solid injection systems can be further categorized into:

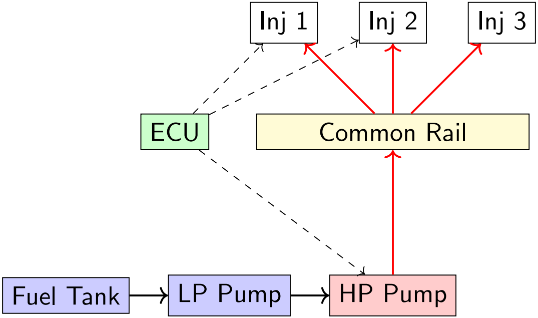
- **Individual Pump and Nozzle System:** Each cylinder has its own dedicated injection pump and nozzle.
- **Unit Injector System:** The pump and nozzle are combined into a single unit for each cylinder, eliminating high-pressure lines.
- **Common Rail System (CRDI):** A single high-pressure pump supplies fuel to a common manifold (rail), which feeds electronically controlled injectors.
- **Distributor System:** A single pump pressurizes and distributes fuel to all cylinders in firing order.

CRDI Concept

CRDI decouples pressure generation from the injection event. Fuel is maintained at very high pressure (up to 2500 bar) in an accumulator (the rail) and injected via solenoid or piezo injectors.

Advantages:

- Injection pressure is independent of engine speed.
- Allows for multiple injections per cycle (pilot, main, post).
- Significant reduction in engine noise and emissions.


Inj 1
Inj 2
Inj 3
ECU
Common Rail
Fuel Tank
LP Pump
HP Pump

The nozzle is the final component that sprays the fuel into the cylinder.

- **Pintle Nozzle:** Has a single central hole. The valve stem has a pin (pintle) that protrudes through the hole, creating a hollow cone spray. Good for avoiding carbon deposits.
- **Multi-hole Nozzle:** Has multiple holes (usually 4 to 8) drilled in a dome-shaped tip. Provides excellent atomization and distribution. Used primarily in direct injection engines.
- **Pintaux Nozzle:** A pintle nozzle with an auxiliary hole for a pilot spray, helping in cold starting.

Modern SI engines have largely replaced carburetors with Electronic Fuel Injection (EFI).

- **TBI (Throttle Body Injection):** A single or pair of injectors situated centrally in the throttle body. (Older technology).
- **MPFI (Multi-Point Fuel Injection):** One injector per cylinder located in the intake manifold just ahead of the intake valve. Ensures equal fuel distribution.
- **GDI (Gasoline Direct Injection):** Fuel is injected directly into the combustion chamber, similar to a diesel engine. Allows for ultra-lean burn and higher compression ratios.

- Sensors (MAF, TPS, O2, Crank position) send data to the Engine Control Unit (ECU).
- The ECU calculates the exact pulse width (open time) for the injectors.
- Fuel is supplied at a constant pressure (around 3 bar) by a fuel pump.
- Injectors spray into the intake ports.

Advantages over Carburetors: Better fuel economy, lower emissions, easier cold starting, and no manifold wetting issues.

GDI Principle

In GDI, the fuel injector is placed inside the cylinder head, injecting gasoline directly into the combustion chamber at high pressures (50-200 bar).

Modes of Operation:

- **Stratified Charge Mode:** Used at light loads. Fuel is injected late in the compression stroke near the spark plug, creating a rich mixture locally while the rest of the cylinder is very lean.
- **Homogeneous Mode:** Used at high loads. Fuel is injected during the intake stroke to mix evenly with air, similar to MPFI.

Feature	MPFI (SI Engine)	CRDI (CI Engine)
Injection Location	Intake Manifold	Direct in Cylinder
Injection Pressure	Low ($\sim 3-5$ bar)	Very High (up to 2500 bar)
Timing Control	Electronic (ECU)	Electronic (ECU)
Atomization Req.	Moderate (vaporizes in manifold)	Extremely High

Table: MPFI vs CRDI

- Fuel injection has revolutionized engine performance and emissions control.
- CI engines require high-pressure direct injection due to in-cylinder combustion physics; CRDI is the modern standard.
- SI engines utilize MPFI for precise metering and are increasingly moving towards GDI for superior efficiency.
- The ECU plays a central role, processing sensor data to determine exact injection timing and duration.

Combustion of fuel inside an IC engine produces temperatures as high as 2000°C to 2500°C.

- Only about 30-40% of this heat is converted into useful work.
- Another 30% is carried away by exhaust gases.
- The remaining 30% is absorbed by engine components (cylinder, piston, valves).

If this heat is not removed, it will cause thermal failure of components and breakdown of the lubricating oil.

If the cooling system fails or is inadequate, several severe issues arise:

- **Lubrication Failure:** Oil viscosity drops, causing metal-to-metal contact and rapid wear.
- **Thermal Stresses:** Unequal expansion can cause seizing of the piston in the cylinder.
- **Pre-ignition / Detonation:** High cylinder head temperatures can prematurely ignite the charge in SI engines.
- **Volumetric Efficiency Drop:** Incoming fresh charge expands rapidly upon hitting hot surfaces, reducing the mass of air entering the cylinder.

Cooling should not be excessive. Overcooling also has detrimental effects:

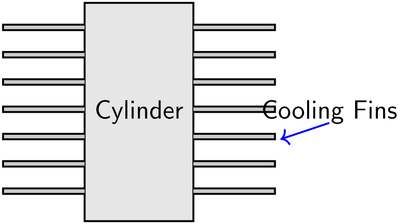
- **Reduced Thermal Efficiency:** Too much heat is carried away by the coolant instead of producing work.
- **Increased Friction:** Lubricating oil becomes too viscous, increasing frictional losses.
- **Poor Vaporization:** In SI engines, fuel may not vaporize properly, leading to poor combustion.
- **Corrosion:** Moisture from combustion can condense on cold cylinder walls, combining with sulfur to form corrosive acids.

There are two primary methods for cooling IC engines:

1. **Air Cooling System:** Heat is dissipated directly to the atmosphere using fins.
2. **Liquid (Water) Cooling System:** A liquid coolant absorbs heat from the engine block and transfers it to the air via a radiator.

- Used mainly in motorcycles, small portable engines, and some aircraft engines.
- The cylinder and cylinder head are provided with extended surfaces called **fins**.
- Fins increase the surface area available for heat transfer.
- Heat transfer rate depends on: fin area, air velocity, and temperature difference.

Advantages: Simple design, lightweight, no coolant leakage problems, warms up quickly.


Cylinder
Cooling Fins

- Used in cars, heavy trucks, and stationary engines.
- The engine block and cylinder head have cast-in passages called **water jackets**.
- Coolant (water + antifreeze) circulates through these jackets, absorbing heat.
- The hot coolant is pumped to a **radiator**, where air blown by a fan removes the heat.
- The cooled liquid is then returned to the engine.

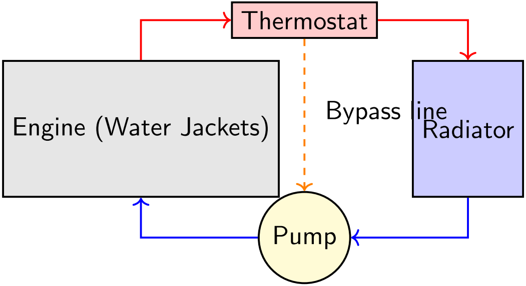
- **Water Jackets:** Passages around cylinders.
- **Water Pump:** Usually a centrifugal pump driven by the engine belt. Circulates the coolant.
- **Radiator:** A heat exchanger with a large surface area (tubes and fins).
- **Cooling Fan:** Pulls air through the radiator, especially useful at low vehicle speeds.
- **Thermostat Valve:** Regulates coolant flow to maintain optimum operating temperature.

Function

A thermostat is a temperature-sensitive valve placed between the engine outlet and the radiator inlet.

Operation:

- **Engine Cold:** Thermostat remains closed. Coolant bypasses the radiator and circulates only within the engine block. This allows the engine to warm up quickly.
- **Engine Hot:** When coolant reaches the operating temperature (e.g., 85°C), the thermostat opens, directing hot coolant to the radiator.


Thermostat
Engine (Water Jackets)
Bypass line
Radiator
Pump

Feature	Air Cooling	Liquid Cooling
Design Complexity	Simple (Fins)	Complex (Jackets, Pump, Radiator)
Weight	Light	Heavy
Temperature Control	Difficult to control precisely	Excellent control (via Thermostat)
Maintenance	Low	High (Leaks, Coolant flush)
Application	Motorcycles, small engines	Cars, trucks, heavy machinery

Pure water is rarely used as a coolant because it freezes at 0°C, causes corrosion, and boils at 100°C.

- **Ethylene Glycol:** Commonly used as an antifreeze. A 50/50 mixture with water drops the freezing point to approx -37°C and raises the boiling point.
- **Anti-corrosion additives:** Prevent rusting of iron components and corrosion of aluminum parts.
- **Lubricants:** Included to lubricate the water pump seal.

Inside an IC engine, many metallic components rub against each other at high speeds (e.g., piston in cylinder, crankshaft in bearings).

- Direct metal-to-metal contact results in enormous friction, heat generation, rapid wear, and ultimate seizure.
- A **lubricating system** introduces a thin film of oil between moving parts to prevent dry friction.

Beyond just reducing friction, engine oil performs several vital roles:

1. **Friction Reduction:** Minimizes wear and power loss.
2. **Cooling Effect:** Absorbs heat from hot components like the underside of the piston and bearings, carrying it back to the oil pan.
3. **Sealing:** Helps piston rings form a gas-tight seal against cylinder walls, preventing blow-by.
4. **Cleaning:** Flushes away microscopic metal wear particles and carbon deposits (via oil filters).
5. **Corrosion Prevention:** Protects internal surfaces from acidic combustion byproducts.

Engine oil must withstand extreme conditions. Key properties include:

- **Viscosity:** The resistance to flow. It must be thick enough to maintain a film at high temperatures, but thin enough to flow during cold starts.
- **Viscosity Index (VI):** Measure of how viscosity changes with temperature. A high VI means less change (highly desirable).
- **Flash Point:** The lowest temperature at which oil vaporizes to form an ignitable mixture. Should be high to prevent burning.
- **Pour Point:** The lowest temperature at which oil can still flow. Important for cold climates.

The Society of Automotive Engineers (SAE) grades oils based on viscosity.

- **Monograde Oils:** (e.g., SAE 30, SAE 40). Viscosity is rated at one specific temperature. Rarely used in modern vehicles.
- **Multigrade Oils:** (e.g., 10W-40, 5W-30). Behave like a thin oil at cold temperatures (W = Winter) and a thicker oil at operating temperatures.
- For SAE 10W-40: It has the cold flow characteristics of a 10W oil, but at 100°C, it protects like an SAE 40 oil.

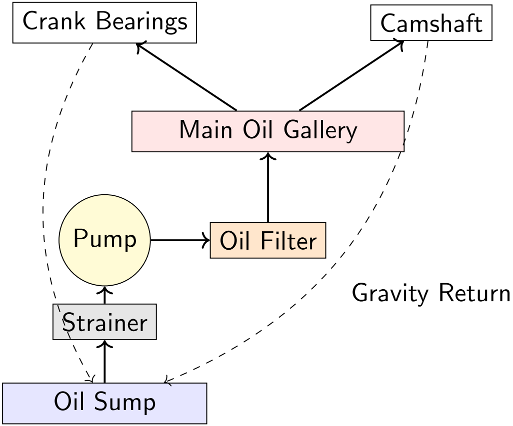
IC engines employ different methods to distribute oil:

1. **Mist Lubrication System** (Used in 2-stroke engines)
2. **Wet Sump Lubrication Systems:**
   - Splash System
   - Pressure Feed System
   - Combined Splash and Pressure System
3. **Dry Sump Lubrication System** (Used in high-performance / race cars)

- Used primarily in small 2-stroke engines (scooters, chainsaws) where the crankcase is used for pre-compressing the air-fuel mixture.
- Therefore, the crankcase cannot store liquid oil.
- **Method:** Lubricating oil (2T oil) is mixed directly with the petrol in a specific ratio (e.g., 2% to 5%).
- As the mixture enters the crankcase, the fuel vaporizes, leaving a mist of oil that lubricates the crank bearings, connecting rod, and cylinder.
- **Drawbacks:** Oil is burned in the combustion chamber, leading to high exhaust smoke and emissions.

- Found in older, low-speed, stationary engines.
- A **dipper** (a scoop) is attached to the bottom of the connecting rod big end.
- As the crankshaft rotates, the dipper dips into an oil trough in the sump and splashes oil vigorously upwards.
- The splashed oil mist covers the cylinder walls, piston pins, and bearings.
- **Limitation:** Not effective for high-speed or highly loaded modern engines, as oil might not reliably reach critical tight-tolerance bearings.

- The standard system for modern automotive engines.
- An oil pump (usually gear-type or rotor-type) draws oil from the sump through a strainer.
- The pump forces oil under high pressure (approx 2 to 4 bar) through an oil filter into the main oil gallery (passages drilled into the block).
- From the main gallery, oil flows under pressure to:
  - Main crankshaft bearings
  - Connecting rod bearings (via holes drilled in the crankshaft)
  - Camshaft bearings and valve mechanism
- Cylinder walls are lubricated by oil squirting out from the sides of the connecting rod bearings.


Crank Bearings
Camshaft
Main Oil Gallery
Pump
Oil Filter
Gravity Return
Strainer
Oil Sump

- Used in high-performance sports cars, racing cars, and aircraft.
- The engine oil sump is kept practically empty (*dry*).
- Requires **two** oil pumps:
    - **Scavenge Pump:** Sucks oil out of the shallow engine sump immediately as it falls and pumps it to an external, tall oil reservoir tank.
    - **Pressure Pump:** Draws oil from the external tank and pumps it into the engine's pressure galleries.

Why use the complex dry sump system?

- **Prevention of Oil Starvation:** Under high cornering, braking, or acceleration G-forces, oil in a standard wet sump sloshes away from the pickup tube. The tall external tank in a dry sump prevents this.
- **Lower Center of Gravity:** The engine sump can be made very shallow, allowing the entire engine to be mounted lower in the chassis.
- **Increased Oil Capacity & Cooling:** The external tank can hold much more oil and acts as an efficient cooler.

System Type	Primary Application
Mist / Petrol Mix	Small 2-stroke engines (scooters)
Splash	Old, slow-speed engines
Pressure Feed	Standard modern passenger cars and commercial vehicles
Dry Sump	High-performance racing cars, aircraft

Table: Lubrication Systems Summary

- In Spark Ignition (SI) engines, the air-fuel mixture does not self-ignite due to compression (unlike CI engines).
- An external source is required to initiate combustion at the end of the compression stroke.
- This is achieved by generating a high-voltage electrical spark across the gap of a spark plug.
- The ignition system must provide a spark of sufficient energy at the exact precise moment relative to the piston position.

A proper ignition system must fulfill these criteria:

1. Provide a sufficiently high voltage (typically 10,000 to 20,000 Volts) to jump the spark plug gap under high compression pressure.
2. Distribute the high voltage to the correct cylinder according to the firing order.
3. Time the spark perfectly to optimize engine power and prevent knocking.
4. Function reliably across a wide range of engine speeds and loads.
5. Be durable and require minimal maintenance.

Historically and practically, ignition systems are categorized as:

- **Battery Ignition System:** Uses a 12V battery as the primary power source. Common in older cars.
- **Magneto Ignition System:** Generates its own electricity using a rotating magnet. Used in aircraft, motorcycles, and small engines without batteries.
- **Electronic Ignition System:** Uses solid-state transistors and ECU control to eliminate mechanical wear. Standard on all modern vehicles.

- **Battery:** Provides the initial low voltage (12V) DC supply.
- **Ignition Switch:** Turns the system ON/OFF.
- **Ignition Coil:** Acts as a step-up transformer to convert 12V into 20,000V. Consists of a Primary winding (thick wire, few turns) and a Secondary winding (thin wire, thousands of turns).
- **Contact Breaker (CB) Points:** A mechanical switch operated by a cam. Makes and breaks the primary circuit.
- **Capacitor (Condenser):** Prevents sparking across the CB points and aids in rapid collapse of the magnetic field.
- **Distributor:** Routes the high voltage to the correct spark plug.

1. When the CB points are closed, current flows through the primary winding of the coil, building a magnetic field.
2. As the engine rotates, the cam pushes the CB points open.
3. This suddenly interrupts the primary current. The magnetic field collapses rapidly.
4. The collapsing field cuts across the thousands of turns in the secondary winding, inducing a massive high voltage (Faraday's Law).
5. This high voltage travels to the distributor rotor, jumps to the correct terminal, and travels to the spark plug to create a spark.

Concept

A magneto system is essentially an electrical generator and ignition coil combined into one unit.

- Contains a rotating permanent magnet driven by the engine.
- The rotating magnetic field induces current directly in the primary winding of the internal coil.
- The rest of the operation (CB points breaking the circuit to induce high voltage in the secondary) is similar to the battery system.
- **Advantage:** No battery required. Very reliable at high speeds.
- **Disadvantage:** Weak spark at very low cranking speeds (hard starting).

Feature	Battery Ignition	Magneto Ignition
Power Source	12V Battery	Engine-driven Magneto
Spark at low speed	Very Good (Easy start)	Poor (Hard start)
Spark at high speed	Decreases (Coil saturation time reduces)	Very Good
Application	Cars, light commercial	2-wheelers, chainsaws, aircraft

Both standard Battery and Magneto systems rely on mechanical Contact Breaker (CB) points.

- **Wear and Tear:** The mechanical rubbing block wears out, changing ignition timing.
- **Pitting:** High currents cause sparking across the points, causing them to pit and burn.
- **Maintenance:** Requires frequent adjustment of the point gap and replacement of points/condenser.
- **High Speed Limitation:** Points can "bounce" at high RPM, causing misfires.

To overcome mechanical issues, modern systems replace the CB points with an electronic trigger.

- Uses a magnetic pickup (Hall effect sensor) or optical sensor to detect crankshaft position.
- The sensor sends a tiny voltage signal to an Electronic Control Unit (ECU) or ignition module.
- The module uses high-power solid-state transistors to switch the primary coil current on and off.
- **Benefits:** No moving parts to wear out, no contact points to pit, zero maintenance, perfectly accurate timing, capable of switching higher primary currents for a hotter spark.

Further evolution eliminated the mechanical distributor.

- **Wasted Spark System:** One ignition coil fires two spark plugs simultaneously (one on compression stroke, one on exhaust stroke). The spark on the exhaust stroke is "wasted".
- **Coil-on-Plug (COP):** Each cylinder has its own individual mini-ignition coil mounted directly on top of the spark plug.
- **Advantages of COP:** Completely eliminates high-tension plug wires (which leak voltage and cause radio interference), precise individual cylinder timing control by the ECU.

Ignition Timing refers to when the spark occurs relative to TDC.

- Combustion takes a finite amount of time (approx 2-3 milliseconds).
- If the spark occurs exactly at TDC, peak pressure happens too late, wasting power.
- Therefore, the spark must be **advanced** (fired before TDC).
- **Speed Advance:** As engine RPM increases, less time is available for combustion, so the spark must be advanced further (done via centrifugal weights or ECU mapping).
- **Load Advance:** At part throttle (low load), the mixture is lean and burns slower, requiring more advance (done via vacuum advance or ECU).

- Ignition systems create the high-voltage spark necessary for SI engines.
- The basic principle is electromagnetic induction via an ignition coil (step-up transformer).
- Traditional systems used mechanical breakers, which suffered from wear and high-speed issues.
- Modern engines use Electronic Ignition and Coil-on-Plug (COP) systems managed by the ECU for maintenance-free, highly optimized operation.

- An engine is designed to run at a certain speed or within a specific speed range.
- When the load on an engine decreases, its speed increases. When the load increases, its speed decreases.
- **Governing** is the process of automatically maintaining the mean engine speed within specified limits whenever there is a variation of load.
- A **Governor** is the mechanical or electronic device that achieves this by regulating the fuel/air supply.

Often confused, these two components serve different purposes regarding speed control:

Flywheel	**Governor**
Controls speed variations during a **single engine cycle** (thermodynamic cycle).	Controls mean speed variations over **many cycles** due to load changes.
Works continuously by storing and releasing kinetic energy.	Operates intermittently, only when there is a change in external load.
Does not alter fuel supply.	Alters the fuel/charge supply.

Depending on the engine type and application, governing is achieved via three primary methods:

1. **Hit and Miss Governing**
2. **Qualitative Governing**
3. **Quantitative Governing**

- Used mainly in very old, slow-speed stationary gas engines.
- **Mechanism:** When the engine speed exceeds the limit (load drops), the governor cuts off the fuel supply entirely for one or more cycles.
- During these "missed" cycles, the engine draws in only air. No explosion occurs, and speed drops.
- When speed falls back to normal, fuel is readmitted ("hit").
- **Disadvantages:** Causes very rough running, high cyclic speed fluctuation, requiring a massively heavy flywheel.

- Used primarily in **CI (Diesel) engines**.
- The **quantity of air** drawn into the cylinder remains constant (no throttle valve).
- The governor controls the **quantity of fuel** injected.
- Therefore, the *quality* (Air-Fuel ratio) of the mixture changes with the load.
- **High load:** More fuel injected (Richer mixture).
- **Low load:** Less fuel injected (Leaner mixture).

- Used primarily in **SI (Petrol) engines**.
- The **quality** (Air-Fuel ratio) remains relatively constant.
- The governor operates a throttle valve that restricts the **quantity of the mixture** entering the cylinder.
- **High load:** Throttle wide open, large volume of mixture enters.
- **Low load:** Throttle mostly closed, small volume of mixture enters.
- **Drawback:** Throttling at part load increases pumping losses, reducing efficiency.

- **Scavenging** is the process of pushing the exhausted gas out of the cylinder of an engine and replacing it with a fresh draft of air (or air-fuel mixture).
- It is particularly critical in **Two-Stroke engines**.
- In a 4-stroke engine, there is a dedicated exhaust stroke where the piston physically pushes the gases out. In a 2-stroke engine, exhaust and intake happen simultaneously near BDC.
- The incoming fresh charge must literally sweep (scavenge) the exhaust gases out of the exhaust port.

Why is perfect scavenging difficult in a 2-stroke engine?

- **Short-circuiting:** The fresh charge might travel straight from the inlet port to the exhaust port and escape without burning.
- **Mixing:** The fresh charge mixes with the exhaust gases, leaving residual burnt gases in the cylinder.
- Result: Reduced power output and high emissions (especially if raw fuel escapes in SI 2-strokes).

To optimize the flow path and prevent short-circuiting, different port arrangements are used:

1. **Cross-flow Scavenging**
2. **Loop (or Reverse flow) Scavenging**
3. **Uniflow Scavenging**

- The inlet (transfer) port and exhaust port are on opposite sides of the cylinder.
- To prevent the incoming charge from shooting straight across and out the exhaust, a **deflector** (a raised ridge) is built onto the crown of the piston.
- The deflector forces the fresh charge upwards toward the cylinder head, pushing the exhaust down and out the opposite side.
- **Disadvantages:** The heavy, oddly shaped piston causes balancing issues and thermal hotspots. Prone to knocking.

- Overcomes the need for a deflector piston (uses a flat or slightly domed piston).
- The transfer ports are angled so that the incoming streams of fresh charge hit the opposite cylinder wall or each other.
- The streams merge, travel up to the cylinder head, loop around, and push the exhaust gases out of the exhaust ports located either below or on the same side.
- **Advantages:** Lighter piston, better heat dissipation, higher speed capability.

The Most Efficient Method

Fresh charge enters at one end of the cylinder and exhaust gases leave at the other end. The flow is in one uniform direction.

- Commonly used in large marine 2-stroke diesel engines.
- Intake is through ports at the bottom of the cylinder (uncovered by the piston).
- Exhaust is through a mechanical poppet valve situated in the cylinder head.
- **Advantages:** Minimum mixing, zero short-circuiting, highest scavenging efficiency.

- The exhaust system safely routes the spent combustion gases from the engine cylinders to the atmosphere.
- **Primary Functions:**
    - Collect exhaust gases from cylinders (Exhaust Manifold).
    - Reduce the high-pressure noise of the exiting gases (Muffler/Silencer).
    - Direct gases away from the vehicle occupants.
    - **Crucially: Reduce harmful pollutants before releasing them.**

Perfect combustion yields only CO_2 and H_2O. Real-world combustion generates harmful emissions:

1. **Carbon Monoxide (CO):** Result of incomplete combustion (lack of oxygen). Highly toxic.
2. **Hydrocarbons (HC):** Unburnt fuel. Reacts with sunlight to form smog.
3. **Nitrogen Oxides (NOx):** Formed when nitrogen and oxygen in the air react at very high combustion temperatures (above 1370°C). Causes acid rain and respiratory issues.
4. **Particulate Matter (PM / Soot):** Microscopic carbon particles, mostly from CI (Diesel) engines.

Pollution reduction is tackled in two ways:

- **In-Cylinder Controls:** Modifying the combustion process to prevent the formation of pollutants (e.g., EGR, varying injection timing).
- **After-Treatment Devices:** Treating the exhaust gases in the exhaust system before they exit the tailpipe (e.g., Catalytic Converters, DPF).

Target: Reducing NOx

NOx formation depends heavily on high peak combustion temperatures.

- **How EGR works:** A valve routes a small portion (5% - 15%) of the inert exhaust gas back into the intake manifold.
- The exhaust gas acts as a heat sink. It does not burn but absorbs heat during combustion.
- This lowers the peak cylinder temperature, significantly reducing NOx formation.
- Widely used in both modern SI and CI engines.

- The most important after-treatment device in modern vehicles.
- Placed in the exhaust pipe, it looks like a muffler but contains a ceramic honeycomb structure.
- The honeycomb is coated with precious metals (Platinum, Palladium, Rhodium) acting as catalysts.
- A catalyst accelerates a chemical reaction without being consumed.
- **Three-Way Catalytic Converter (TWC):** Used in SI engines. It tackles three pollutants simultaneously: CO, HC, and NOx.

The TWC performs two types of reactions simultaneously: **1. Reduction**

(Targeting NOx) Rhodium catalyst strips oxygen from NOx. $2NO \rightarrow N_2 + O_2$ **2. Oxidation (Targeting CO and HC)**

Platinum/Palladium forces CO and HC to react with the released oxygen (and exhaust oxygen). $2CO + O_2 \rightarrow 2CO_2$ $HC + O_2 \rightarrow CO_2 + H_2O$

- A Three-Way Catalyst requires a precise environment to perform both Reduction (needs rich mixture) and Oxidation (needs lean mixture) simultaneously.
- It only works efficiently within a very narrow window around the **Stoichiometric Air-Fuel ratio** (14.7:1 for petrol).
- If the engine runs lean, NOx reduction fails. If rich, CO/HC oxidation fails.
- This is why modern cars use an **Oxygen (O2 / Lambda) Sensor** in the exhaust to continuously adjust fuel injection in a closed-loop system.

Diesel engines run very lean, meaning there is too much oxygen in the exhaust for a standard Three-Way Catalyst to reduce NOx. Diesels require different devices:

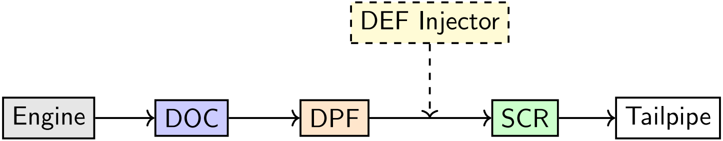
1. **Diesel Oxidation Catalyst (DOC):** Oxidizes CO and HC into CO_2 and H_2O.
2. **Diesel Particulate Filter (DPF):** Traps and burns off soot (PM).
3. **Selective Catalytic Reduction (SCR):** Uses a chemical reductant (AdBlue / Urea) to destroy NOx.

- A ceramic filter with alternately blocked channels, forcing exhaust gas through porous walls.
- It physically traps microscopic soot particles (PM).
- Over time, the filter fills up and creates backpressure.
- **Regeneration:** The engine periodically raises exhaust temperatures (often by late fuel injection) to burn the trapped soot into ash and CO_2, clearing the filter.

The modern solution for Diesel NOx

SCR can reduce NOx emissions by up to 90%.

- A fluid called **Diesel Exhaust Fluid (DEF) / AdBlue** (32.5% urea, 67.5% water) is injected into the exhaust pipe upstream of the SCR catalyst.
- Heat turns the urea into Ammonia (NH_3).
- Inside the SCR catalyst, the ammonia reacts with NOx to form harmless Nitrogen (N_2) and Water vapor (H_2O).



This complex sequence is required to meet the stringent Bharat Stage 6 (BS6) emission norms.

- IC engines produce harmful pollutants: CO, HC, NOx, and PM.
- **EGR** reduces peak temperatures to lower NOx inside the cylinder.
- **Three-Way Catalysts (TWC)** are the standard for Petrol engines, neutralizing CO, HC, and NOx simultaneously when operating near stoichiometry.
- **Diesel engines** require complex exhaust systems comprising DOC (for CO/HC), DPF (for Soot), and SCR with AdBlue injection (for NOx).

- In a normal (Naturally Aspirated) engine, the piston moving down creates a vacuum, sucking air into the cylinder.
- The maximum pressure of air entering is limited by atmospheric pressure (approx 1 bar).
- The amount of fuel you can burn—and thus the power generated—is limited by the amount of oxygen (air) drawn into the cylinder.
- To get more power, you could build a larger engine, but that adds weight and size.

Solution

Force air into the cylinder at a pressure higher than atmospheric pressure.

- Compressing the incoming air increases its density.
- Denser air means more oxygen enters the cylinder.
- More oxygen allows more fuel to be injected and burned per cycle.
- Result: A significant increase in power output from the same engine displacement.
- This process is called **Supercharging** or **Forced Induction**.

Both perform the same basic function (compressing intake air), but they differ in how the compressor is driven:

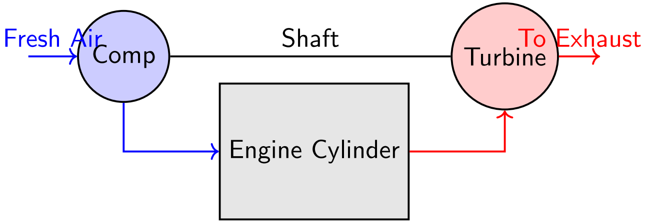
- **Supercharger:** Driven mechanically by the engine crankshaft via a belt, gear, or chain.
- **Turbocharger:** Driven pneumatically by the waste energy (heat and pressure) of the escaping exhaust gases.

- Typically use Roots-type blowers, twin-screw compressors, or centrifugal compressors.
- **Advantages:**
  - Immediate boost response (no "lag").
  - Excellent low-RPM power generation.
- **Disadvantages:**
  - Parasitic load: The supercharger steals engine power to spin. It can consume up to 20% of engine power at high RPMs.
  - Reduces overall thermal efficiency compared to turbocharging.

A turbocharger consists of two halves joined by a common shaft:

1. **Turbine (Hot side):** Placed in the exhaust stream. Hot, expanding exhaust gases strike the turbine blades, spinning it at very high speeds (up to 200,000 RPM).
2. **Compressor (Cold side):** Placed in the intake tract. Connected to the turbine via a shaft, it spins at the same speed, drawing in atmospheric air, compressing it, and forcing it into the engine.

It recovers "waste" energy from the exhaust, making it highly efficient.


Fresh Air
Comp
Shaft
Turbine
To Exhaust
Engine Cylinder

The primary drawback of Turbochargers

Turbo lag is the delay between pressing the accelerator and feeling the surge of power.

- When engine speed is low, exhaust gas flow is low.
- The turbine doesn't spin fast enough to create significant boost.
- When the throttle is opened, it takes a few moments for exhaust gases to build up, spin the heavy turbine wheel, and pressurize the intake manifold.

Modern engineering uses several techniques to minimize lag:

- **Smaller Turbos:** Have less inertia, spooling up faster (but provide less peak power).
- **Twin-Turbo Systems:** Using a small turbo for low RPMs and a larger one for high RPMs (Sequential twin-turbo).
- **Twin-Scroll Turbos:** Separates exhaust pulses from different cylinders to maintain high kinetic energy hitting the turbine.
- **Variable Geometry Turbochargers (VGT):** Uses adjustable vanes to direct exhaust gas flow.

- The turbine housing contains movable vanes controlled by the ECU.
- **At low engine speeds:** Vanes close partially, acting like a nozzle. This accelerates the slow exhaust gases, spinning the turbine faster (reducing lag).
- **At high engine speeds:** Vanes open fully to allow massive exhaust flow without creating excessive backpressure.
- VGT provides optimum boost across the entire RPM range.

- When air is compressed (by a supercharger or turbocharger), its temperature increases significantly.
- Hot air is less dense. If fed directly to the engine, it negates the benefit of forced induction and severely increases the risk of engine knock (detonation).
- **Intercooler:** A heat exchanger (like a radiator) placed between the compressor and the engine.
- It cools the compressed air using ambient air (Air-to-Air) or engine coolant (Air-to-Water).
- Cooling the air makes it denser, allowing even more mass of air into the cylinder.

- A turbocharger can theoretically keep spinning faster and creating more pressure until the engine blows up (over-boosting).
- A **Wastegate** is a safety valve on the exhaust turbine housing.
- When intake boost pressure reaches a safe preset maximum limit, the wastegate opens.
- It bypasses some exhaust gases around the turbine, preventing it from spinning any faster, thus controlling maximum boost.

Feature	Supercharger	Turbocharger
Power Source	Mechanical (Belt driven)	Pneumatic (Exhaust driven)
Lag	Zero (Instant)	Present (Spool up time)
Efficiency	Low (Parasitic loss)	High (Recovers waste energy)
Application	Drag cars, muscle cars	Most modern diesel & petrol cars

Both systems require Intercoolers to maximize air density and prevent knocking.

Introduction to Performance Testing

- Performance tests are conducted to evaluate the capabilities of an engine.
- The objective is to determine power output, fuel economy, and efficiencies.
- These parameters allow comparison between different engine designs.
- Helpful in diagnosing faults and improving future designs.

Objectives of Performance Testing

- To determine the maximum power developed by the engine.
- To determine the mechanical and thermal efficiencies.
- To plot performance curves (e.g., specific fuel consumption vs. load).
- To evaluate emissions and ensure they meet regulatory standards.

Basic Performance Parameters

- Brake Power (BP): Power available at the engine crankshaft.
- Indicated Power (IP): Power developed inside the cylinder.
- Frictional Power (FP): Power lost to friction ($FP = IP - BP$).
- Specific Fuel Consumption (SFC): Fuel consumed per unit of power produced.

Measurement of Engine Speed

- Engine speed is measured in revolutions per minute (RPM).
- It is a critical parameter for calculating power output.
- Measured using mechanical or electrical tachometers.
- Stroboscopes can also be used for non-contact measurement.

Types of Tachometers

- **Mechanical Tachometers**: Use centrifugal force to move an indicator.
- **Electrical Tachometers**: Generate a voltage proportional to speed.
- **Magnetic Pickup**: Counts gear teeth passing a magnetic sensor.
- **Optical Encoders**: Use light pulses for highly accurate digital measurement.

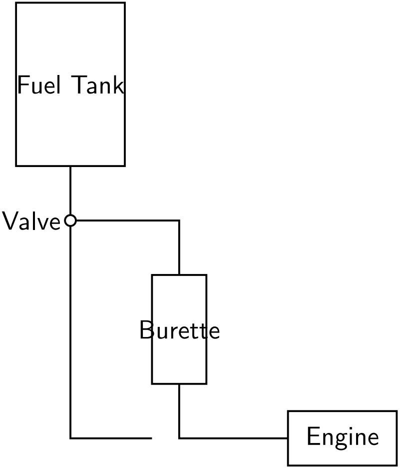
Measurement of Fuel Consumption

- Crucial for evaluating the economy of the engine.
- Can be measured on a volumetric or gravimetric basis.
- For steady-state testing, time taken to consume a known quantity of fuel is noted.
- Mass of fuel consumed per unit time gives the fuel consumption rate (m_f).

Volumetric Method (Burette Method)

- A glass bulb of known volume is connected in the fuel line.
- The engine draws fuel from the bulb.
- A stopwatch measures the time taken to empty the bulb.
- Fuel density is used to convert volume to mass.

Volumetric Fuel Measurement Setup



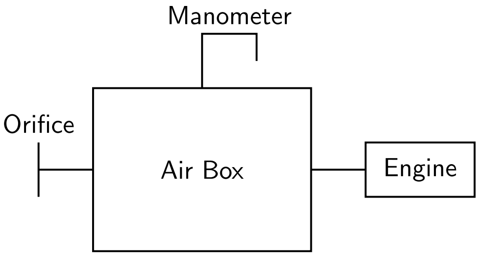
Gravimetric Method

- Measures the actual mass of fuel consumed.
- Fuel tank is placed on a sensitive weighing scale.
- Time required to consume a specific mass of fuel is recorded.
- More accurate than volumetric method as it avoids density variations due to temperature.

Measurement of Air Consumption

- Required to determine the air-fuel ratio.
- Air flow into IC engines is pulsating, not steady.
- Direct measurement using orifice is inaccurate due to pulsations.
- An air box (surge tank) is used to damp out the pulsations.

Air Box Method



Calculation of Air Consumption

- Pressure drop across the orifice is measured using a U-tube manometer.
- Volume of air flow: $V_a = C_d \cdot A \cdot \sqrt{2gh_a}$
- Where C_d is the coefficient of discharge.
- h_a is the head of air in meters.
- Mass of air: $m_a = V_a \cdot \rho_a$

Measurement of Brake Power

- Brake Power (BP) is the actual power available at the crankshaft.
- It is always less than the Indicated Power (IP) due to friction.
- BP is measured using devices called dynamometers.
- The engine is coupled to the dynamometer which absorbs or transmits the power.

Types of Dynamometers

- Dynamometers are broadly classified into two types:
- **1. Absorption Dynamometers:** These absorb the power produced by the engine and convert it into heat.
- **2. Transmission Dynamometers:** These measure power while transmitting it to a load.

Absorption Dynamometers

- Commonly used for routine engine testing.
- Simple in construction and operation.
- Examples include:
- Prony brake dynamometer
- Rope brake dynamometer
- Hydraulic dynamometer
- Eddy current dynamometer

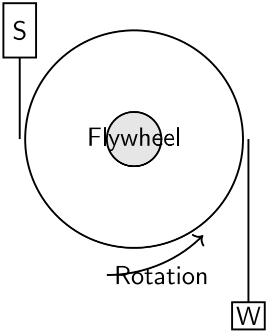
Prony Brake Dynamometer

- Consists of wooden blocks clamped around the engine flywheel.
- Friction between blocks and flywheel absorbs power.
- A lever arm is attached to the blocks, and a weight is placed at the end.
- Cooling is required as friction generates significant heat.

Rope Brake Dynamometer

- A rope is wound around the engine flywheel.
- One end is attached to a dead weight (W) and the other to a spring balance (S).
- Friction between the rope and flywheel absorbs power.
- Effective braking load is $(W - S)$.

Rope Brake Diagram



Calculation of BP from Rope Brake

- Braking Torque, $T = (W - S) \times R_e$
- Where R_e is the effective radius $= (D + d)/2$
- $D =$ Diameter of flywheel, $d =$ diameter of rope.
- $W =$ Dead weight (N), $S =$ Spring balance reading (N).
- Brake Power, $BP = \frac{2\pi NT}{60000}$ kW

Hydraulic Dynamometer

- Uses fluid friction to absorb power.
- Consists of an impeller driven by the engine, rotating in a water-filled casing.
- Power is absorbed by the momentum transfer to the water.
- Heat generated is carried away by a continuous flow of water.

Eddy Current Dynamometer

- Uses electromagnetic induction to absorb power.
- A rotor is turned by the engine inside a magnetic field.
- Eddy currents are induced in the rotor, creating opposing torque.
- Power absorption is controlled by varying the electromagnet's current.

Transmission Dynamometers

- Measure torque without absorbing power.
- Often use strain gauges mounted on the transmission shaft.
- The twist in the shaft is proportional to the torque.
- Highly accurate and allow continuous measurement under actual load.

Summary of BP Measurement

- Accurate measurement of Torque (T) and Speed (N) is essential.
- $BP = \frac{2\pi NT}{60}$ Watts
- Selection of dynamometer depends on engine size, speed range, and testing duration.
- Cooling is a major consideration for absorption dynamometers.

Comparison of Dynamometers

Type	Advantages	Disadvantages
Rope Brake	Simple, cheap	Cooling issues, low accuracy
Hydraulic	High capacity, good cooling	Needs water supply
Eddy Current	Highly accurate, easy control	Expensive, needs power supply

Measurement of Indicated Power

- Indicated Power (IP) is the total power developed by combustion.
- It is determined from an Indicator Diagram (p-V diagram).
- The diagram shows pressure variations inside the cylinder during the cycle.
- The area of the indicator diagram represents the work done per cycle.

Indicator Diagram

- Obtained using a mechanical or electronic engine indicator.
- **Mean Effective Pressure (MEP or p_m)**: The constant theoretical pressure that would produce the same work per cycle.
- $p_m = \frac{\text{Area of indicator diagram}}{\text{Length of diagram}} \times \text{Spring constant}$
- Unit of p_m is typically bar or N/m^2.

Calculation of IP

- Formula: $IP = \frac{p_m \cdot L \cdot A \cdot n \cdot K}{60000}$ kW
- p_m = Indicated mean effective pressure (N/m^2)
- L = Stroke length (m)
- A = Cross-sectional area of piston (m^2)
- n = Number of working strokes per minute (N for 2-stroke, $N/2$ for 4-stroke)
- K = Number of cylinders

Measurement of Friction Power (FP)

- Friction Power is the power lost to overcome friction between moving parts.
- It also includes pumping losses (drawing in air, expelling exhaust).
- Basic relation: $IP = BP + FP$
- Several methods exist to determine FP.

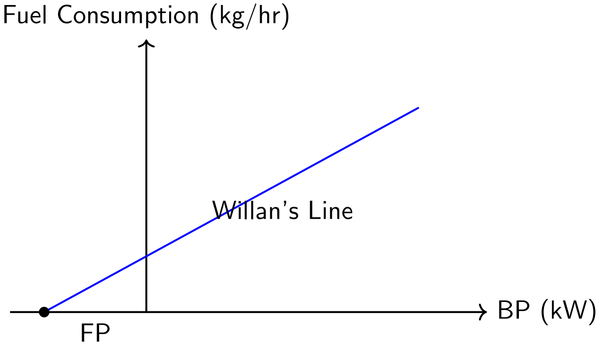
Methods to Determine FP

- **1. Willan's Line Method**: Extrapolation of fuel consumption vs BP line.
- **2. Morse Test**: Applicable to multi-cylinder engines only.
- **3. Motoring Test**: Driving the engine with an electric motor.
- **4. Retardation Test**: Measuring deceleration rate of the engine.

Willan's Line Method

- Also known as Fuel Rate Extrapolation method.
- A plot is made of Fuel Consumption (kg/hr) vs Brake Power (BP).
- At constant speed, this plot is essentially a straight line.
- The line is extrapolated to zero fuel consumption.

Willan's Line Diagram



Limitations of Willan's Line

- Suitable only for Compression Ignition (CI) engines.
- Not suitable for SI engines because mixture strength varies with load.
- Assumes friction remains constant at different loads (at constant speed).
- Extrapolation can introduce errors.

Morse Test

- Used for multi-cylinder engines.
- The engine is run at a constant speed and the total BP is measured.
- One cylinder is 'cut-off' (ignition or fuel stopped).
- The load is reduced to bring the speed back to the original value.
- The new BP is measured.

Morse Test Calculation

- Let total $BP = BP_T$.
- When cylinder 1 is cut, the measured BP is BP_1.
- The IP of cylinder 1 is: $IP_1 = BP_T - BP_1$.
- This is repeated for all cylinders to find $IP_1, IP_2, \dots$
- Total $IP = IP_1 + IP_2 + \cdots + IP_k$.
- Then, $FP = IP - BP_T$.

Motoring Test

- Engine is first run under normal firing conditions until operating temperatures are reached.
- Fuel supply is abruptly cut off.
- A swinging-field dynamometer is immediately switched to motor the engine.
- The power required to motor the engine at the same speed is measured.
- This power is taken as the Friction Power (FP).

Retardation Test

- Engine is run to a speed above the test speed.
- Fuel is cut off and the time taken for speed to drop by a certain amount is noted.
- The test is repeated with a known extra load applied.
- By comparing the deceleration times, FP can be calculated.
- Requires knowledge of the moment of inertia of rotating parts.

Engine Efficiencies

- Efficiencies are used to compare the performance of different engines.
- They indicate how well the engine converts fuel energy into useful work.
- Major types of efficiencies:
- Mechanical Efficiency
- Thermal Efficiency (Indicated and Brake)
- Volumetric Efficiency
- Relative Efficiency

Mechanical Efficiency (η_m)

- Ratio of Brake Power (BP) to Indicated Power (IP).
- It indicates the effectiveness of the engine in overcoming friction.
- $\eta_m = \frac{BP}{IP} = \frac{BP}{BP+FP}$
- Values typically range from 70% to 90%.
- It decreases with an increase in engine speed due to higher friction.

Thermal Efficiency

- Ratio of work output to the heat energy supplied by the fuel.
- Heat supplied $= m_f \times CV$
- Where $m_f =$ mass of fuel consumed per second (kg/s).
- $CV =$ Calorific Value of the fuel (J/kg or kJ/kg).
- Can be based on Indicated Power or Brake Power.

Indicated Thermal Efficiency (η_{ith})

- Based on the power developed inside the cylinder (IP).
- $\eta_{ith} = \frac{IP}{Heat\ \ Supplied} = \frac{IP}{m_f \times CV}$
- Where IP is in kW, m_f in kg/s, and CV in kJ/kg.
- Shows the efficiency of the combustion process and cycle.

Brake Thermal Efficiency (η_{bth})

- Based on the useful power available at the crankshaft (BP).
- $\eta_{bth} = \frac{BP}{Heat\ \ Supplied} = \frac{BP}{m_f \times CV}$
- Also called overall efficiency of the engine.
- Relationship: $\eta_{bth} = \eta_{ith} \times \eta_m$

Relative Efficiency

- Also known as Efficiency Ratio.
- Ratio of actual thermal efficiency to air-standard efficiency.
- $\eta_{rel} = \frac{\text{Actual Thermal Efficiency}}{\text{Air-Standard Efficiency}}$
- Actual thermal efficiency can be based on IP or BP.
- Indicates how close the actual cycle approaches the ideal theoretical cycle.

Volumetric Efficiency (η_v)

- Applies mainly to naturally aspirated engines.
- Ratio of actual volume of air drawn to swept volume.
- $\eta_v = \frac{V_a}{V_s}$
- Where V_a = actual volume of air inhaled per cycle.
- V_s = swept volume of the cylinder.

Alternative Definition of Volumetric Efficiency

- Can also be defined in terms of mass.
- $\eta_v = \frac{m_a}{\rho_a \times V_s \times n \times K}$
- Where m_a = actual mass of air consumed per minute.
- ρ_a = density of ambient air.
- V_s = swept volume, n = cycles per minute, K = number of cylinders.

Specific Fuel Consumption (SFC)

- Mass of fuel consumed per unit of power developed per hour.
- Used to compare fuel economy of different engines.
- Indicated Specific Fuel Consumption: $ISFC = \frac{m_f}{IP}$ (kg/kWh)
- Brake Specific Fuel Consumption: $BSFC = \frac{m_f}{BP}$ (kg/kWh)

Relationship between SFC and Efficiency

- Efficiency and SFC are inversely related.
- $\eta_{bth} = \frac{3600}{BSFC \times CV}$
- (Assuming BSFC is in kg/kWh and CV in kJ/kg).
- A lower SFC implies a higher thermal efficiency.

Factors Affecting Volumetric Efficiency

- Valve timing (opening and closing angles).
- Valve lift and port design.
- Intake manifold design (flow resistance).
- Engine speed (higher speed generally reduces η_v).
- Exhaust gas residual.

Summary of Efficiencies

Parameter	**Formula**
Mechanical Efficiency	$\frac{BP}{IP}$
Brake Thermal Efficiency	$\frac{BP}{m_f \times CV}$
Relative Efficiency	$\frac{\eta_{th}}{\eta_{air-standard}}$
Volumetric Efficiency	$\frac{\text{Actual Air Vol}}{\text{Swept Vol}}$

Heat Balance Sheet

- An account of the heat energy supplied by the fuel.
- Shows how this energy is distributed among various components.
- Typically measured over a specific time (e.g., per minute or per hour).
- Helps identify areas where energy losses can be reduced.

Components of Heat Balance

- 1. Total heat supplied by the fuel.
- 2. Heat equivalent to useful work (Brake Power).
- 3. Heat rejected to the cooling medium (water or air).
- 4. Heat carried away by exhaust gases.
- 5. Unaccounted heat losses (radiation, convection, etc.).

1. Heat Supplied by Fuel (Q_s)

- This is the input energy to the engine.
- Calculated from the mass of fuel consumed and its calorific value.
- $Q_s = m_f \times CV$
- Where m_f is fuel consumption in kg/min.
- CV is the calorific value in kJ/kg.
- Unit of Q_s is kJ/min.

2. Heat Equivalent to Brake Power (Q_{BP})

- The portion of heat converted into useful mechanical work.
- BP is measured in kW (which is kJ/s).
- To convert to kJ/min: $Q_{BP} = BP \times 60$
- This represents the useful output of the engine.

3. Heat Rejected to Cooling Water (Q_w)

- Heat carried away by the engine cooling system.
- Calculated using the mass flow rate of water and its temperature rise.
- $Q_w = m_w \times C_{pw} \times (T_{wo} - T_{wi})$
- m_w = mass flow rate of cooling water (kg/min).
- C_{pw} = specific heat of water (4.18 kJ/kgK).
- T_{wi}, T_{wo} = inlet and outlet water temperatures.

4. Heat Carried Away by Exhaust Gases (Q_g)

- Heat lost to the atmosphere through exhaust.
- $Q_g = m_g \times C_{pg} \times (T_g - T_a)$
- m_g = mass of exhaust gas = $m_a + m_f$ (kg/min).
- C_{pg} = specific heat of exhaust gas.
- T_g = exhaust gas temperature.
- T_a = ambient temperature.

5. Unaccounted Heat Losses (Q_u)

- Heat lost due to radiation and convection from engine surfaces.
- Heat lost due to incomplete combustion.
- Heat lost to lubricating oil (if not measured separately).
- Calculated by difference: $Q_u = Q_s - (Q_{BP} + Q_w + Q_g)$.

Typical Heat Distribution (SI Engine)

- Useful Work (BP): 25 - 30%
- Cooling Water: 25 - 30%
- Exhaust Gases: 30 - 40%
- Unaccounted Losses: 5 - 10%
- Note: Values vary with load, speed, and engine design.

Typical Heat Distribution (CI Engine)

- Useful Work (BP): 30 - 40%
- Cooling Water: 25 - 30%
- Exhaust Gases: 25 - 35%
- Unaccounted Losses: 5 - 10%
- CI engines generally have higher thermal efficiency than SI engines.

Heat Balance Sheet Table Format

Item	**Heat (kJ/min)**	**%**
Heat Supplied (Q_s)	10000	100
Heat to BP (Q_{BP})	3000	30
Heat to Cooling (Q_w)	3000	30
Heat to Exhaust (Q_g)	3500	35
Unaccounted (Q_u)	500	5
Total	**10000**	**100**

Importance of Heat Balance

- Provides a clear picture of engine efficiency.
- Highlights the magnitude of various losses.
- Guides engineers in designing waste heat recovery systems.
- Helps in sizing the radiator and cooling system.

Summary

- A heat balance sheet is a first law of thermodynamics analysis.
- Energy In = Energy Out.
- Accurate measurement of fuel, air, and temperatures is critical.
- Unaccounted losses serve as a check on measurement accuracy.

Performance Characteristics

- Graphical representations of engine performance.
- Show how parameters change with speed or load.
- Help in understanding engine behavior under various operating conditions.
- Crucial for matching the engine to its application (e.g., vehicle, generator).

Variable Speed Test

- Engine is run at full throttle (or full load setting for CI).
- Speed is varied by changing the load on the dynamometer.
- Parameters measured: Torque, BP, SFC.
- Plotted against Engine Speed (RPM).

Torque vs. Speed Curve

- Torque increases initially with speed, reaches a peak, then declines.
- Peak torque occurs at the speed where volumetric efficiency is highest.
- At higher speeds, friction increases and breathing becomes restricted, reducing torque.
- Important for vehicle acceleration.

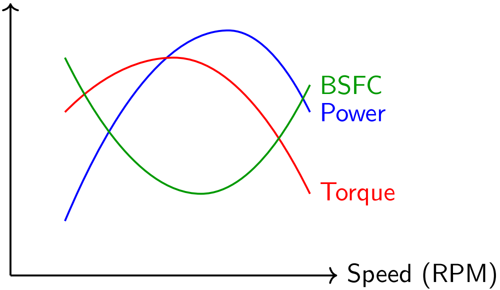
Power vs. Speed Curve

- Brake Power (BP) increases with speed initially ($BP \propto N \times T$).
- Reaches a maximum at a speed higher than the peak torque speed.
- Eventually drops off sharply because torque drops faster than speed increases.
- Maximum power dictates the engine's top speed capabilities.

BSFC vs. Speed Curve

- Brake Specific Fuel Consumption (BSFC) has a 'U' shape.
- High at low speeds due to heat loss to cylinder walls (longer time).
- Reaches a minimum at mid-range speeds (most efficient operation).
- Increases at high speeds due to disproportionate increase in friction.

Typical Speed Characteristics



Constant Speed Test (Load Test)

- Engine speed is kept constant (e.g., using a governor).
- Load is varied from zero to maximum.
- Typical for generator sets.
- Parameters plotted against Brake Power or Load percentage.

Characteristics under Load

- Mechanical efficiency increases with load (friction is roughly constant).
- Brake Thermal Efficiency increases with load, reaches a peak near full load.
- BSFC decreases as load increases, minimizing near full load.
- At very high loads, rich mixtures (in SI) cause BSFC to rise again.

Volumetric Efficiency Characteristic

- Generally highest at low to medium speeds.
- Drops at high speeds due to flow friction in valves and manifolds.
- Limits the maximum power an engine can produce.
- Can be improved by tuning intake manifolds or using variable valve timing.

SI vs CI Engine Characteristics

- **CI Engines**: Flatter torque curves, better low-end torque.
- Lower BSFC across all speeds compared to SI.
- **SI Engines**: Higher maximum speeds, higher peak power per unit weight.
- Torque drops more sharply outside the optimum speed range.

Factors Affecting Performance

- Compression Ratio: Higher CR increases thermal efficiency and power.
- Air-Fuel Ratio: Lean mixtures give better economy; rich mixtures give more power.
- Ignition/Injection Timing: Must be optimized for speed and load.
- Ambient Conditions: High temperature and altitude reduce air density, dropping power.

Conclusion of Testing

- Performance testing provides a complete map of engine capabilities.
- Testing standards (e.g., SAE, ISO) ensure comparability.
- Results are used to optimize engine design and tuning.
- Critical for emissions compliance and fuel economy certification.

Introduction to Alternative Fuels

- Fuels other than conventional petroleum-based diesel and gasoline.
- Used to power IC engines.
- Can be derived from renewable sources or abundant natural resources.
- Include alcohols, gaseous fuels, biodiesel, and hydrogen.

Need for Alternative Fuels

- **Depletion of Fossil Fuels**: Crude oil reserves are finite.
- **Environmental Concerns**: Need to reduce greenhouse gas emissions.
- **Energy Security**: Reducing dependence on imported crude oil.
- **Economic Factors**: Stabilizing fuel prices through local production.

Desirable Properties of Alternative Fuels

- High energy density (calorific value).
- Good combustion characteristics (octane/cetane rating).
- Low emissions (CO, HC, NOx, Particulates).
- Safe to handle, store, and transport.
- Cost-competitive with conventional fuels.

Alcohols (Methanol and Ethanol)

- Methanol (CH3OH) can be produced from coal, natural gas, or biomass.
- Ethanol (C2H5OH) is primarily produced by fermenting sugars from crops (corn, sugarcane).
- Can be used pure or blended with gasoline (e.g., E10, E85).
- Excellent fuels for SI engines due to high octane rating.

Advantages of Alcohols

- High octane number allows higher compression ratios (more power/efficiency).
- Contains oxygen, leading to cleaner combustion and lower CO/HC emissions.
- High latent heat of vaporization cools the intake charge, increasing volumetric efficiency.
- Renewable if produced from biomass.

Disadvantages of Alcohols

- Low energy density (requires larger fuel tanks).
- Corrosive to certain metals and plastics in the fuel system.
- Cold starting problems due to high latent heat.
- Invisible flame (methanol) poses a safety hazard.

Biodiesel

- Produced from vegetable oils or animal fats via transesterification.
- Properties are very similar to conventional diesel.
- Can be used in existing CI engines without major modifications.
- Often blended with diesel (e.g., B20 = 20% biodiesel).

Pros and Cons of Biodiesel

- **Pros**: Renewable, biodegradable, non-toxic, higher cetane number, provides lubricity.
- **Pros**: Lower particulate and CO emissions.
- **Cons**: Slightly lower energy content, higher viscosity at low temperatures.
- **Cons**: Can increase NOx emissions slightly; potential food vs. fuel conflict.

Natural Gas (CNG)

- Composed primarily of Methane (CH4).
- Stored as Compressed Natural Gas (CNG) at high pressures (200 bar).
- High octane number (around 120), suitable for high CR SI engines.
- Very clean burning, produces low CO2 and virtually no particulates.

Liquefied Petroleum Gas (LPG)

- Mixture of Propane and Butane.
- Stored as a liquid under moderate pressure.
- Higher energy density than CNG (takes up less space).
- Good octane rating, widely used in modified SI engines.

Biogas

- Produced by anaerobic digestion of organic matter (waste, manure).
- Contains mostly Methane and CO2.
- Requires purification (removal of CO2 and H2S) before engine use.
- Highly renewable and helps in waste management.

Properties Comparison

Fuel	Octane/Cetane	Energy Content (MJ/kg)
Gasoline	90-98 (ON)	44
Diesel	45-55 (CN)	43
Ethanol	108 (ON)	27
CNG	120 (ON)	50
Biodiesel	50-60 (CN)	37

Introduction to Fuel Rating

- Fuel rating determines the anti-knock quality of a fuel.
- Knocking (or detonation) is abnormal combustion causing a metallic sound.
- It limits the maximum compression ratio and thus engine power and efficiency.
- Different rating scales are used for SI (Gasoline) and CI (Diesel) engines.

Knocking in SI Engines

- Occurs at the end of the combustion process.
- Unburnt 'end gas' auto-ignites before the flame front reaches it.
- Causes high pressure waves that ping against cylinder walls.
- Can cause severe mechanical damage and overheating.

Octane Number (ON)

- The standard measure of a fuel's resistance to knock in an SI engine.
- Higher octane number means greater resistance to knocking.
- Based on a comparison with two primary reference fuels (PRFs).
- Determined using a standard CFR (Cooperative Fuel Research) engine.

Primary Reference Fuels for SI

- **Iso-octane ($C8H18$)**: Highly resistant to knock. Assigned ON = 100.
- **Normal heptane ($C7H16$)**: Knocks very easily. Assigned ON = 0.
- Octane Number is the percentage by volume of iso-octane in a mixture with n-heptane that matches the knocking behavior of the test fuel.

Types of Octane Ratings

- **Research Octane Number (RON)**: Tested under mild conditions (low speed). Represents city driving.
- **Motor Octane Number (MON)**: Tested under severe conditions (high speed, high load). Represents highway driving.
- **Anti-Knock Index (AKI)**: Average of RON and MON, $(R + M)/2$. Commonly displayed on fuel pumps.

Knocking in CI Engines

- Occurs at the beginning of the combustion process.
- Caused by a long ignition delay.
- Too much fuel accumulates before ignition, burning rapidly all at once.
- Results in a sudden pressure spike and characteristic 'diesel knock'.

Cetane Number (CN)

- The standard measure of ignition quality of diesel fuel.
- A higher cetane number means a shorter ignition delay.
- Shorter delay means smoother combustion and less knock.
- Also based on two primary reference fuels.

Primary Reference Fuels for CI

- **Normal Cetane ($C16H34$)**: Ignites very easily (short delay). Assigned CN = 100.
- **Alpha-methyl naphthalene ($C11H10$)**: Very poor ignition quality. Assigned CN = 0.
- (Note: Heptamethylnonane with CN = 15 is often used now instead of alpha-methyl naphthalene).
- Cetane Number is the percentage of n-cetane in the equivalent mixture.

Comparison of SI and CI Requirements

- SI engines need fuels that resist auto-ignition (High Octane).
- CI engines need fuels that auto-ignite easily (High Cetane).
- A good SI fuel is a very poor CI fuel, and vice versa.
- Octane and Cetane numbers are inversely related.

Fuel Additives for Rating Improvement

- **Anti-knock agents (SI)**: Historically TEL (Tetraethyl lead) was used, now banned due to toxicity.
- Modern alternatives: MTBE, Ethanol, Toluene.
- **Ignition accelerators (CI)**: Alkyl nitrates or nitrites are added to boost Cetane number.

Diesel Index

- An inexpensive, calculated alternative to Cetane Number.
- Based on physical properties rather than engine testing.
- $DI = \frac{\text{Aniline Point } (^\circ\text{F}) \times \text{API Gravity}}{100}$
- Provides a rough estimate of ignition quality.

Summary of Fuel Rating

Parameter	SI Engines	CI Engines
Rating Scale	Octane Number	Cetane Number
Desired Property	Resist auto-ignition	Easy auto-ignition
Good Fuel PRF	Iso-octane (100)	n-Cetane (100)
Bad Fuel PRF	n-Heptane (0)	α-methyl naphthalene (0)

Introduction to Engine Emissions

- IC engines are major contributors to air pollution.
- Ideal combustion produces only CO_2 and H_2O.
- Real combustion is incomplete and occurs at high temperatures.
- This leads to the formation of harmful pollutants.

Major Pollutants from IC Engines

- 1. Unburnt Hydrocarbons (HC or UHC)
- 2. Carbon Monoxide (CO)
- 3. Oxides of Nitrogen (NOx)
- 4. Particulate Matter (PM) or Smoke
- 5. Oxides of Sulfur (SOx) - depends on fuel sulfur content.

Unburnt Hydrocarbons (HC)

- Result of incomplete combustion.
- Causes: flame quenching near cold cylinder walls, rich mixtures, misfires.
- Effects: Smog formation, some hydrocarbons are carcinogenic.
- Higher in SI engines compared to CI engines.

Carbon Monoxide (CO)

- A toxic, colorless, odorless gas.
- Formed primarily due to a lack of oxygen (rich mixture).
- Mainly a problem in SI engines operating rich for power or cold starts.
- CI engines operate lean, so CO emissions are generally low.

Oxides of Nitrogen (NOx)

- Mainly NO and NO2.
- Formed at very high combustion temperatures (above 1500\degree C).
- Nitrogen and oxygen from the air react.
- Effects: Acid rain, smog formation, respiratory issues.
- A major challenge for CI engines running lean and hot.

Particulate Matter (PM)

- Tiny solid or liquid particles (soot, ash, unburnt lube oil).
- Primarily a problem in CI (Diesel) engines due to heterogeneous combustion.
- Formed in fuel-rich zones within the diesel spray.
- Can penetrate deep into the lungs causing severe health issues.

Emission Trade-offs

- Engine tuning often involves trade-offs.
- **NOx vs. PM in Diesel**: Advancing injection timing reduces PM but increases peak temperature, thus increasing NOx.
- **CO/HC vs. NOx in Gasoline**: Lean mixtures reduce CO/HC but can increase NOx until the mixture is too lean to burn hot.

Emission Control: Engine Design

- Optimizing combustion chamber shape (e.g., swirl generation).
- Electronic Fuel Injection (EFI) for precise air-fuel ratio control.
- Multi-valve technology for better breathing.
- High-pressure common rail systems (CRDI) in diesel for finer atomization.

Exhaust Gas Recirculation (EGR)

- Used primarily to reduce NOx emissions.
- Recirculates a portion of exhaust gas back into the intake.
- The inert exhaust gas acts as a heat sink.
- Lowers peak combustion temperatures, thereby reducing NOx formation.

Catalytic Converters (SI Engines)

- Placed in the exhaust system to treat gases after combustion.
- **Three-Way Catalytic Converter (TWC)**:
- 1. Reduces NOx to Nitrogen and Oxygen.
- 2. Oxidizes CO to CO2.
- 3. Oxidizes HC to CO2 and H2O.
- Requires operation near stoichiometric air-fuel ratio.

Diesel Aftertreatment Systems

- **Diesel Oxidation Catalyst (DOC)**: Oxidizes CO and HC.
- **Diesel Particulate Filter (DPF)**: Traps and burns off soot/PM.
- **Selective Catalytic Reduction (SCR)**: Injects urea (AdBlue) to reduce NOx into Nitrogen and water.
- Essential for meeting modern emission norms (e.g., Euro 6, BS VI).

Emission Norms

- Government regulations limit the allowable tailpipe emissions.
- Examples: Euro standards in Europe, Bharat Stage (BS) in India.
- Norms become progressively stricter over time.
- Drive the development of advanced engine and aftertreatment technologies.

Lecture 2.19

Thermal Engineering-II

Need for Exhaust Gas Analysis

- To determine the actual air-fuel ratio supplied to the engine.
- To evaluate combustion efficiency.
- To check the emission levels of harmful pollutants.
- To diagnose engine faults (e.g., rich or lean mixtures).

Major Exhaust Emissions

- Unburned Hydrocarbons (HC)
- Carbon Monoxide (CO)
- Oxides of Nitrogen (NO_x)
- Particulate Matter (PM) or Soot
- Carbon Dioxide (CO_2) and Water Vapor (H_2O) - products of complete combustion

Composition of Exhaust Gases

Component	SI Engine	CI Engine
CO	High	Low
HC	High	Low
NOx	Moderate	High
PM	Low	High

Methods of Measurement

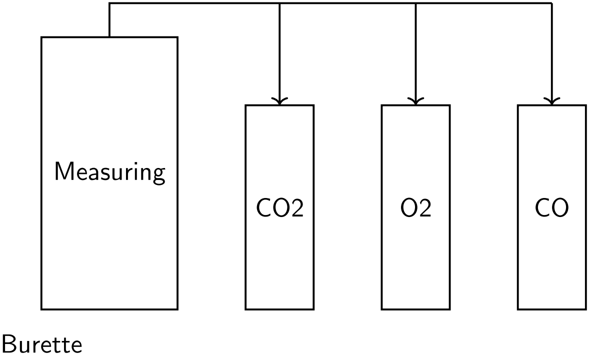
- Chemical absorption methods (e.g., Orsat Apparatus)
- Non-Dispersive Infrared (NDIR) analyzers for CO and CO2
- Flame Ionization Detector (FID) for HC
- Chemiluminescence Analyzer (CLA) for NOx
- Smoke meters for Particulate Matter

Orsat Apparatus - Introduction

- The Orsat apparatus is a piece of laboratory equipment used to analyze a gas sample.
- It measures the volumetric fractions of CO2, O2, and CO in exhaust gases.
- It is based on the principle of volumetric absorption.
- Remaining gas is assumed to be Nitrogen (N2).

Principle of Volumetric Absorption

- A known volume of gas is sequentially passed through chemical solutions.
- Each solution absorbs a specific gas component.
- The decrease in volume after each absorption gives the volume of that specific gas.
- Measurements are taken at constant temperature and pressure.


Measuring
CO2
O2
CO
Burette

Chemical Reagents in Orsat

- Flask 1 (for CO2): Potassium Hydroxide (KOH) solution.
- Flask 2 (for O2): Alkaline solution of Pyrogallic acid.
- Flask 3 (for CO): Ammoniacal Cuprous Chloride solution.

Order of Absorption

- The order of passing the gas is crucial: CO_2, then O_2, then CO.
- Reason: Alkaline pyrogallol (for O_2) also absorbs CO_2.
- Ammoniacal cuprous chloride (for CO) absorbs both CO_2 and O_2.
- Therefore, CO_2 must be removed first, followed by O_2.

Limitations of Orsat Apparatus

- Measures only on a dry basis (water vapor condenses).
- Cannot measure unburned hydrocarbons (HC) or NOx.
- Requires skilled operator; process is relatively slow.
- Accuracy depends on the freshness of chemical solutions.

Summary of Lecture 19

- Exhaust gas analysis is essential for engine performance and emission control.
- Major pollutants are CO, HC, NOx, and PM.
- Orsat apparatus uses volumetric absorption to measure CO2, O2, and CO.
- The order of absorption (CO2 -¿ O2 -¿ CO) is strictly maintained.

Lecture 2.20

Thermal Engineering-II

Review of Orsat Apparatus

- Used for volumetric analysis of dry exhaust gases.
- Measures CO2, O2, and CO sequentially.
- Chemicals used: KOH, Alkaline Pyrogallol, Ammoniacal Cuprous Chloride.
- Provides results on a volumetric (molar) basis.

Preparation for Testing

- The measuring burette is surrounded by a water jacket to maintain constant temperature.
- A leveling bottle containing water (or brine) is used to draw in and push out the gas.
- The system must be purged to remove atmospheric air before taking the sample.
- Exactly 100 cc of the gas sample is drawn into the burette.

Step 1: Measuring CO_2

- The 100 cc sample is pushed into the first flask containing Potassium Hydroxide (KOH).
- It is allowed to sit for a few minutes for absorption.
- The gas is drawn back into the burette using the leveling bottle.
- The reduction in volume directly gives the percentage of CO_2.

Chemical Reaction for CO2 Absorption

$$2KOH + CO_2 \rightarrow K_2CO_3 + H_2O$$

Potassium hydroxide reacts with carbon dioxide to form potassium

carbonate and water.

Step 2: Measuring O2

- The remaining gas is pushed into the second flask containing Alkaline Pyrogallol.
- This chemical absorbs Oxygen (O2).
- The gas is returned to the burette and the new volume is measured.
- The further reduction in volume gives the percentage of O2.

Step 3: Measuring CO

- The remaining gas is pushed into the third flask containing Ammoniacal Cuprous Chloride.
- This absorbs Carbon Monoxide (CO).
- The gas is returned to the burette and the final volume is measured.
- The final reduction in volume gives the percentage of CO.

Chemical Reaction for CO Absorption

$$Cu_2Cl_2 + 2CO + 2H_2O \rightarrow Cu_2Cl_2 \cdot 2CO \cdot 2H_2O$$

Ammoniacal cuprous chloride forms a complex compound with

carbon monoxide.

Determining Nitrogen Content

- The Orsat apparatus does not have a chemical to absorb Nitrogen (N_2).
- N_2 is inert and does not react with the solutions.
- The remaining volume of gas after all three absorptions is assumed to be Nitrogen.
- \% N2 = 100 - (\% CO2 + \% O2 + \% CO)

Calculations from Orsat Analysis

- Convert volumetric fractions to mass fractions if required.
- Determine the actual air-fuel (A/F) ratio from the exhaust composition.
- Compare actual A/F ratio with stoichiometric A/F ratio to find excess air.
- Identify if the mixture was rich or lean.

Significance of Results

- High O_2 indicates lean mixture or misfire.
- High CO indicates rich mixture and incomplete combustion.
- High CO_2 indicates good combustion efficiency (operating near stoichiometric).
- Calculations help in engine tuning.

Summary of Lecture 20

- Orsat apparatus procedure involves sequential absorption in three specific chemicals.
- It measures CO2, O2, and CO by volume reduction.
- Nitrogen is found by difference.
- The data is crucial for determining actual air-fuel ratio and combustion quality.

Lecture 2.21

Thermal Engineering-II

Need for Advanced Analyzers

- Orsat apparatus is slow and cannot measure trace gases like HC and NOx accurately.
- Modern emission norms require continuous and highly accurate measurement.
- Electronic analyzers provide real-time data.
- They are capable of measuring very low concentrations (ppm levels).

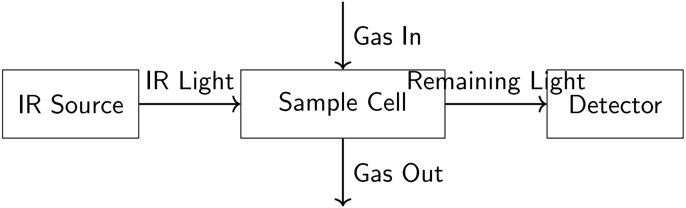
Non-Dispersive Infrared (NDIR) Analyzer

- Used primarily to measure CO, CO2, and sometimes HC.
- Principle: Gases absorb infrared light at specific, characteristic wavelengths.
- "Non-dispersive" means it does not use a prism or grating to separate light.
- It uses optical filters to select the specific wavelength of interest.

Working Principle of NDIR

- An infrared source emits a broad spectrum of IR light.
- The light passes through a sample cell containing the exhaust gas.
- The target gas (e.g., CO) absorbs light at its specific wavelength.
- A detector measures the amount of light that passes through.
- Less light hitting the detector means higher gas concentration.

NDIR Block Diagram



Advantages of NDIR

- Continuous, real-time measurement.
- High sensitivity and accuracy.
- Non-destructive testing.
- Specific to the target gas (minimal interference if properly filtered).

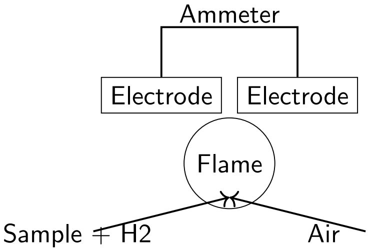
Flame Ionization Detector (FID)

- Used to measure total Unburned Hydrocarbons (HC).
- Highly sensitive to hydrocarbon compounds.
- Widely used in automotive emission testing to meet regulatory standards.
- Measures concentration in parts per million of Carbon (ppmC).

Working Principle of FID

- The sample gas is introduced into a hydrogen flame.
- Hydrocarbons present in the sample burn in the flame and produce ions.
- An electric field is applied across the flame.
- The ions migrate to the electrodes, creating a small electric current.
- The current is proportional to the number of carbon atoms in the hydrocarbons.

FID Block Diagram



Advantages of FID

- Extremely high sensitivity (can measure ppb levels).
- Fast response time.
- Linear response over a wide range of concentrations.
- Relatively insensitive to other gases like CO, CO2, and water vapor.

Comparison: NDIR vs FID

- NDIR is physical (absorption of light), FID is chemical/electrical (ionization).
- NDIR used for CO/CO2; FID exclusively for HC.
- NDIR is simpler and cheaper; FID requires hydrogen fuel gas.

Summary of Lecture 21

- Modern analyzers provide continuous, accurate emission data.
- NDIR uses infrared absorption to measure CO and CO2.
- FID uses a hydrogen flame to ionize hydrocarbons and measures the resulting current.
- Both are essential for modern engine testing and certification.

Lecture 2.22

Thermal Engineering-II

Measurement of Oxides of Nitrogen (NOx)

- NOx consists mainly of NO (Nitric Oxide) and NO2 (Nitrogen Dioxide).
- It is a major pollutant causing smog and acid rain.
- Produced at high temperatures in the combustion chamber.
- Standard measurement method: Chemiluminescence Analyzer (CLA).

Chemiluminescence Analyzer (CLA) Principle

- Chemiluminescence is the emission of light as a result of a chemical reaction.
- The reaction between Nitric Oxide (NO) and Ozone (O3) produces light.
- The intensity of the emitted light is proportional to the NO concentration.
- CLA measures NO directly; NO2 must be converted to NO first to measure total NOx.

CLA Chemical Reaction

$$NO + O_3 \rightarrow NO_2^* + O_2$$

$$NO_2^* \rightarrow NO_2 + h\nu \text{ (light)}$$

The excited NO2 molecule decays to ground state, emitting a

photon.

Working of CLA

- Exhaust sample is passed through a converter (if measuring total NOx) to reduce NO2 to NO.
- Sample enters a reaction chamber and mixes with ozone generated internally.
- A photomultiplier tube (PMT) detects the emitted light.
- The signal is amplified and displayed as NO/NOx concentration.

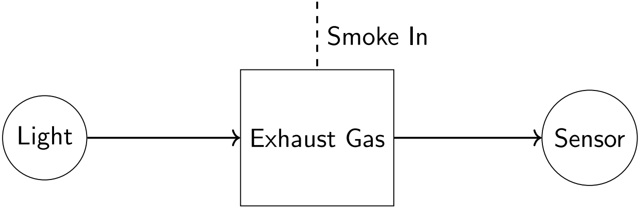
Measurement of Particulate Matter (Smoke)

- Smoke or soot is primarily an issue with Diesel (CI) engines.
- It consists of carbon particles, unburned hydrocarbons, and ash.
- Measurement methods include Optical Smoke Meters and Filter Paper methods.
- Important for visibility, health, and environmental regulations.

Optical Smoke Meter (Opacimeter)

- Measures the opacity of the exhaust gas.
- A light beam is passed across the exhaust stack or sample cell.
- A detector on the other side measures the light intensity.
- Smoke particles scatter and absorb the light.
- The reduction in light intensity indicates the smoke level (opacity %).

Opacimeter Principle Diagram



Filter Paper Method (Bosch Smoke Meter)

- A fixed volume of exhaust gas is drawn through a specific filter paper.
- The soot particles darken the paper.
- A reflectometer measures the darkness of the paper.
- Results are given on the Bosch Smoke Scale (0 to 10, where 0 is clean and 10 is completely black).

Comparison of Smoke Measurement

- Opacimeters provide continuous, real-time measurement; good for transient testing.
- Filter paper method provides a discrete average reading.
- Opacimeters are standard for regulatory testing worldwide.
- Filter methods are simpler and used for quick field checks.

Summary of Gas Analyzers

- CO/CO_2: Non-Dispersive Infrared (NDIR)
- HC: Flame Ionization Detector (FID)
- NO_x: Chemiluminescence Analyzer (CLA)
- Smoke/Particulates: Opacimeter or Filter Paper

Summary of Lecture 22

- CLA relies on the light-emitting reaction between NO and Ozone.
- CLA requires converting NO2 to NO to measure total NOx.
- Smoke is measured via optical opacity or physical filtration.
- This completes our study of exhaust gas analysis methods.

Lecture 3.23

Thermal Engineering-II

What is Refrigeration?

- Refrigeration is the science of producing and maintaining temperatures below that of the surrounding atmosphere.
- It involves removing heat from a space or object and transferring it to another environment.
- A system that accomplishes this is called a refrigerator.
- The substance used to absorb and reject heat is called a refrigerant.

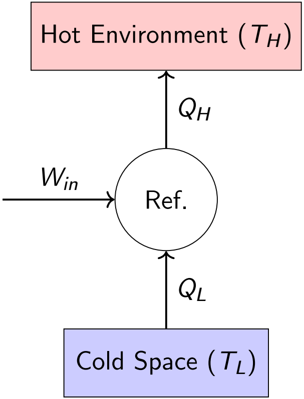
Applications of Refrigeration

- Food processing and preservation (cold storage, supermarkets).
- Chemical and pharmaceutical industries (maintaining reaction temperatures).
- Air conditioning of buildings and vehicles.
- Liquefaction of gases (O2, N2, etc.).
- Manufacturing processes (e.g., cooling molds).

Thermodynamics of Refrigeration

- Heat naturally flows from a high-temperature body to a low-temperature body (Clausius statement).
- To reverse this process, external work must be supplied to the system.
- Refrigerators operate on a reversed heat engine cycle.
- They absorb heat (Q_L) at low temperature (T_L) and reject heat (Q_H) at high temperature (T_H) by consuming work (W).

Refrigerator Block Diagram



Unit of Refrigeration

- The capacity of a refrigeration system is expressed in 'Tons of Refrigeration' (TR).
- One TR is defined as the rate of heat removal required to freeze 1 ton (2000 lbs) of water at $0^\circ C$ into ice at $0^\circ C$ in 24 hours.
- 1 TR = 210 kJ/min = 3.5 kW (approximately).
- This unit dates back to the era of harvesting ice.

Coefficient of Performance (COP)

- Efficiency of a refrigerator is expressed as COP.
- COP = (Desired Effect) / (Work Input)
- Desired Effect = Cooling Effect (Q_L)
- COP $= Q_L/W_{in}$
- Since $W_{in} = Q_H - Q_L$ (from First Law), COP $= Q_L/(Q_H - Q_L)$.

Ideal vs Actual COP

- For a reversible Carnot refrigerator:
- COP_{Carnot} $= T_L/(T_H - T_L)$
- Temperatures must be in absolute scale (Kelvin).
- Actual COP is always less than Carnot COP due to irreversibilities.
- COP can be greater than 1 (unlike efficiency).

Heat Pump vs Refrigerator

- A heat pump uses the exact same cycle as a refrigerator.
- The difference is the purpose (desired effect).
- Refrigerator goal: Maintain a cold space (Desired effect $= Q_L$).
- Heat pump goal: Maintain a hot space (Desired effect $= Q_H$).
- COP_{HP} $= Q_H / W_{in}$

Relation between COP of Refrigerator and Heat Pump

$$COP_{HP} = \frac{Q_H}{W_{in}}$$

$$W_{in} = Q_H - Q_L \Rightarrow Q_H = W_{in} + Q_L$$

$$COP_{HP} = \frac{W_{in} + Q_L}{W_{in}} = 1 + \frac{Q_L}{W_{in}}$$

$$COP_{HP} = 1 + COP_{ref}$$

Methods of Refrigeration

- Ice Refrigeration (melting ice absorbs heat).
- Evaporative Cooling (water evaporates absorbing latent heat).
- Expansion of Gases (air refrigeration cycle).
- Vapor Compression System (most common, uses phase change).
- Vapor Absorption System (uses heat energy instead of mechanical work).

Summary of Lecture 23

- Refrigeration transfers heat from a lower to higher temperature, requiring work.
- Capacity is measured in Tons of Refrigeration (TR).
- Performance is measured by COP (Cooling effect / Work input).
- COP of a heat pump is always 1 greater than a refrigerator operating between same limits.

Lecture 3.24

Thermal Engineering-II

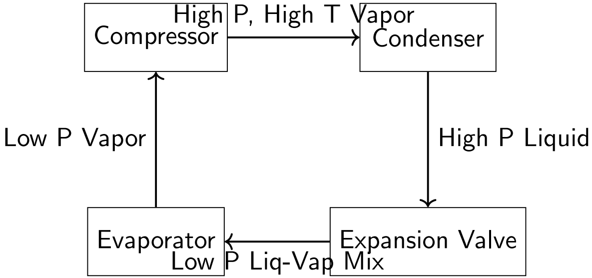
Introduction to VCRS

- VCRS stands for Vapor Compression Refrigeration System.
- It uses a circulating liquid refrigerant as the medium to absorb and remove heat.
- It undergoes phase changes (liquid to vapor and vapor to liquid).
- It is used in household refrigerators, air conditioners, and large industrial chillers.

Components of VCRS

- The system consists of four main components:
- 1. Compressor
- 2. Condenser
- 3. Expansion Valve (or Capillary Tube)
- 4. Evaporator

VCRS Schematic Diagram



1. Compressor

- Function: To compress the low-pressure, low-temperature refrigerant vapor to a high-pressure, high-temperature vapor.
- Requires work input (usually from an electric motor).
- Creates the pressure difference necessary for the refrigerant to circulate.
- Often referred to as the 'heart' of the system.

2. Condenser

- Function: To reject heat to the surroundings (cooling medium, usually air or water).
- The high-temperature vapor enters the condenser.
- As it loses heat, it condenses back into a high-pressure liquid.
- The heat rejected equals the heat absorbed in the evaporator plus the compressor work.

3. Expansion Valve

- Function: To reduce the pressure of the high-pressure liquid.
- Acts as a throttling device.
- Process is isenthalpic (constant enthalpy).
- As pressure drops, a portion of the liquid flashes into vapor, cooling the remaining mixture.
- Controls the flow rate of refrigerant into the evaporator.

4. Evaporator

- Function: To absorb heat from the refrigerated space.
- The low-pressure, low-temperature liquid-vapor mixture enters.
- It absorbs heat and evaporates entirely into a vapor.
- This is where the actual 'cooling effect' takes place.
- The resulting vapor then goes back to the compressor.

Thermodynamic Processes in VCRS

- Process 1-2: Isentropic Compression in the compressor.
- Process 2-3: Isobaric Heat Rejection in the condenser.
- Process 3-4: Isenthalpic Expansion in the expansion valve.
- Process 4-1: Isobaric Heat Addition in the evaporator.

Why an Expansion Valve instead of a Turbine?

- In a reversed Carnot cycle, a turbine is used for expansion to recover work.
- In actual VCRS, an expansion valve (throttling device) is used.
- Reason: The work recovered by a liquid expanding in a turbine is very small.
- The cost and complexity of a turbine are not justified by the minimal energy recovery.

Ideal vs Simple VCRS

- Ideal cycle assumes completely reversible compression and heat transfer without pressure drops.
- Simple cycle (standard rating cycle) acknowledges the irreversible throttling process.
- Assumes vapor leaves the evaporator as saturated vapor.
- Assumes liquid leaves the condenser as saturated liquid.

Summary of Lecture 24

- VCRS consists of Compressor, Condenser, Expansion Valve, and Evaporator.
- Refrigerant changes phase to efficiently transfer heat.
- Compression is isentropic, condensation/evaporation are isobaric, expansion is isenthalpic.
- It is the most practical and widely used refrigeration cycle.

Lecture 3.25

Thermal Engineering-II

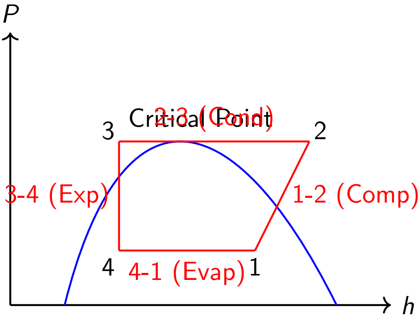
Property Diagrams in Refrigeration

- To analyze system performance, we plot the cycle on property diagrams.
- The two most common diagrams are:
- 1. Temperature-Entropy (T-s) diagram
- 2. Pressure-Enthalpy (P-h) diagram
- P-h diagram is preferred by engineers because it makes calculating heat and work very easy.

The P-h Diagram

- Y-axis is Pressure (P), usually on a logarithmic scale.
- X-axis is Enthalpy (h).
- Shows the saturated liquid line and saturated vapor line meeting at the critical point.
- Region inside the dome is the liquid-vapor mixture region.
- Left of dome is subcooled liquid; right of dome is superheated vapor.

Standard VCRS on P-h Diagram



Enthalpy Values at State Points

- State 1: Saturated vapor at evaporator pressure ($h_1 = h_{g,evap}$).
- State 2: Superheated vapor at condenser pressure (h_2 found from superheat tables/charts).
- State 3: Saturated liquid at condenser pressure ($h_3 = h_{f,cond}$).
- State 4: Mixture at evaporator pressure ($h_4 = h_3$ due to isenthalpic expansion).

Performance Calculations

- With enthalpy values known, we can calculate system performance.
- Refrigerating Effect (RE) = Heat absorbed in evaporator.
- $\text{RE} = h_1 - h_4$ (kJ/kg)
- Compressor Work (W_c) = Enthalpy change during compression.
- $W_c = h_2 - h_1$ (kJ/kg)

Calculating COP

- Coefficient of Performance is the ratio of desired effect to work input.
- COP = RE / W_c
- COP $= (h_1 - h_4)/(h_2 - h_1)$
- Since $h_3 = h_4$, we can also write:
- COP $= (h_1 - h_3)/(h_2 - h_1)$

Other Performance Parameters

- Heat Rejected in Condenser $(Q_c) = h_2 - h_3$ (kJ/kg)
- Note that $Q_c = RE + W_c$
- Mass Flow Rate of Refrigerant (m):
- $m =$ Cooling Load (in kW) / RE (in kJ/kg)
- Resulting m is in kg/s.

Compressor Power

- Theoretical Power Required $= m \times W_c$
- Power $= m \times (h_2 - h_1)$ (kW)
- If compressor has isentropic efficiency (η_{iso}) and mechanical efficiency (η_m):
- Actual Power $=$ Theoretical Power / $(\eta_{iso} \times \eta_m)$

Summary of Equations

Parameter	Formula (kJ/kg)
Refrigerating Effect	$h_1 - h_4$
Compressor Work	$h_2 - h_1$
Heat Rejected	$h_2 - h_3$
COP	$\frac{h_1 - h_4}{h_2 - h_1}$

Why P-h Diagram is Preferred

- Horizontal lines represent constant pressure processes (evaporation and condensation).
- Vertical lines represent constant enthalpy processes (throttling).
- Energy quantities (RE, Work, Heat) are simply horizontal distances (differences in enthalpy).
- Makes visual analysis and calculation highly straightforward.

Summary of Lecture 25

- Performance of VCRS is best analyzed using the P-h diagram.
- Enthalpy values at the four state points determine all energy transfers.
- COP is calculated as $(h_1 - h_4)/(h_2 - h_1)$.
- Mass flow rate links specific energy (kJ/kg) to system capacity (kW).

Lecture 3.26

Thermal Engineering-II

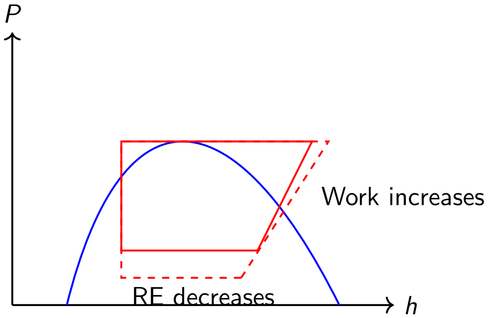
Operating Conditions

- The standard cycle assumes ideal conditions.
- In reality, operating conditions fluctuate.
- We need to understand the effect of:
- 1. Decreasing Evaporator Pressure
- 2. Increasing Condenser Pressure
- 3. Superheating of Vapor
- 4. Subcooling of Liquid

Effect of Decreasing Evaporator Pressure

- If evaporator pressure drops (e.g., to reach a lower temperature):
- 1. Refrigerating Effect (RE) decreases because h_1 slightly decreases and specific volume increases.
- 2. Compressor Work increases because the pressure ratio (P_{cond}/P_{evap}) is higher.
- Result: Significant drop in COP.

P-h Diagram: Decrease in Evaporator Pressure



Effect of Increasing Condenser Pressure

- If condenser pressure rises (e.g., due to hotter ambient air):
- 1. Refrigerating Effect (RE) decreases because h_3 (and thus h_4) increases.
- 2. Compressor Work increases due to higher discharge pressure.
- Result: COP decreases. Compressor discharge temperature also rises.

Effect of Superheating the Vapor

- Superheating occurs when vapor absorbs heat in the evaporator beyond the saturated state before entering the compressor.
- Effect on RE: RE increases (absorbs more heat).
- Effect on Work: Specific volume of vapor increases, increasing work required.
- Effect on COP: Depends on the specific refrigerant. Can slightly increase or decrease COP.

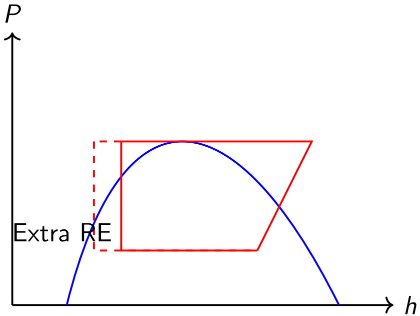
Why Superheat Intentionally?

- Despite mixed effects on COP, we often intentionally superheat (by 5 to 10 degrees).
- Reason: To ensure that absolutely NO liquid droplets enter the compressor.
- Liquid is incompressible; liquid entering a compressor will cause severe mechanical damage (liquid slugging).
- Safety over slight efficiency changes.

Effect of Subcooling the Liquid

- Subcooling occurs when liquid is cooled below its saturation temperature before the expansion valve.
- Effect on RE: h_3 (and h_4) decreases significantly, so RE $(h_1 - h_4)$ increases.
- Effect on Work: Compressor work remains unchanged.
- Result: COP definitely increases.

P-h Diagram: Subcooling



How is Subcooling Achieved?

- By utilizing a larger condenser surface area.
- By passing the liquid line through cooler ambient air.
- By using a Liquid-Vapor heat exchanger (subcools liquid while superheating vapor).
- Subcooling is highly desirable for improving efficiency.

Summary of Parameter Effects

- Evaporator pressure down -¿ COP down
- Condenser pressure up -¿ COP down
- Subcooling -¿ COP UP (always desirable)
- Superheating -¿ COP effect varies, but necessary for compressor safety.

Summary of Lecture 26

- Operating pressures greatly dictate system efficiency.
- Keep evaporator pressure as high as possible for the required temperature.
- Keep condenser pressure as low as possible.
- Subcooling improves COP, while superheating prevents compressor damage.

Lecture 3.27

Thermal Engineering-II

Problem Statement

- A standard VCRS uses R-134a and operates between condenser pressure of 1.0 MPa and evaporator pressure of 0.14 MPa.
- The cooling load is 10 TR.
- Assume saturated vapor leaves the evaporator and saturated liquid leaves the condenser.
- Find: (a) COP, (b) Mass flow rate of refrigerant, (c) Compressor power.

Step 1: Extract Properties from Tables

- From R-134a tables at $P_{evap} = 0.14$ MPa (approx -18.8 \ensuremath{^\circ}C):
- $h_1 = h_g = 239.16$ kJ/kg
- $s_1 = s_g = 0.94456$ kJ/kg.K
- From R-134a tables at $P_{cond} = 1.0$ MPa (approx 39.4 \ensuremath{^\circ}C):
- $h_3 = h_f = 107.32$ kJ/kg
- Therefore, $h_4 = h_3 = 107.32$ kJ/kg.

Step 2: Find state 2 (Compressor Exit)

- Process 1-2 is isentropic, so $s_2 = s_1 = 0.94456$ kJ/kg.K
- At $P_2 = 1.0$ MPa, we look at superheated tables for R-134a to find the enthalpy where $s = 0.94456$.
- Interpolating tables, we find $h_2 \approx 275.39$ kJ/kg.

Step 3: Calculate Specific Energies

- Refrigerating Effect (RE) $= h_1 - h_4$
- RE $= 239.16 - 107.32 = 131.84$ kJ/kg
- Compressor Work $(W_c) = h_2 - h_1$
- $W_c = 275.39 - 239.16 = 36.23$ kJ/kg

Step 4: Calculate COP

- COP = RE / W_c
- COP = 131.84/36.23
- COP = 3.64
- This means for every 1 kW of electrical power, the system provides 3.64 kW of cooling.

Step 5: Convert Load and Find Mass Flow Rate

- Cooling Load = 10 TR
- Convert TR to kW: 1 TR $\approx$ 3.517 kW
- Total Cooling Capacity $= 10 \times 3.517 = 35.17$ kW (kJ/s)
- Mass flow rate (m) = Total Capacity / RE
- $m = 35.17/131.84 = 0.2668$ kg/s

Step 6: Calculate Compressor Power

- Theoretical Compressor Power $(P) = m \times W_c$
- P $= 0.2668$ kg/s $\times$ 36.23 kJ/kg
- P $= 9.66$ kW
- This is the theoretical power required by the compressor.

What if there is Subcooling?

- If the problem stated "liquid is subcooled by 5\ensuremath{^\circ}C before expansion":
- We would find h_3 at $P_{cond} = 1.0$ MPa and $T = T_{sat} - 5 = 39.4 - 5 = 34.4^\circ C$.
- This lowers h_3 (and h_4), increasing RE and increasing COP.
- Mass flow rate would also decrease since each kg absorbs more heat.

What if there is Isentropic Efficiency?

- If the problem stated "compressor isentropic efficiency is 80%":
- Actual Work = Isentropic Work / 0.80
- Actual Work $= 36.23/0.80 = 45.29$ kJ/kg
- Actual COP $= 131.84/45.29 = 2.91$
- Actual Power $= m \times$ Actual Work $= 12.08$ kW

Final Results Summary

Parameter	Value
COP	3.64
Mass Flow Rate	0.2668 kg/s
Compressor Power	9.66 kW

Summary of Lecture 27

- Solving VCRS problems is a systematic procedure.
- Identify state points and extract enthalpies from property tables.
- Calculate RE and Work.
- Use system capacity to link specific properties to actual mass flow rates and power.

Introduction to VCRS Applications

- Vapor Compression Refrigeration Systems (VCRS) are the most widely used refrigeration systems.
- They are used in both domestic and industrial applications.
- Key applications include: domestic refrigerators, air conditioning, cold storage, and ice plants.
- They operate on the reversed Carnot cycle with practical modifications.

Domestic Refrigerators

- Used for food preservation and cooling beverages.
- Typically use a hermetically sealed compressor.
- Evaporator is located in the freezer section.
- Condenser is usually a natural convection type at the back of the unit.

Water Coolers

- Provide chilled water for drinking purposes.
- Two main types: Storage type and Instantaneous type.
- Storage type cools water in a tank over time.
- Instantaneous type cools water as it flows through the evaporator coils.

Ice Plants

- Commercial facilities for large scale ice production.
- Ammonia (NH3) is commonly used as the primary refrigerant.
- Brine (saltwater) is often used as a secondary refrigerant.
- Ice is formed in cans submerged in the chilled brine.

Cold Storage

- Large scale facilities for long term storage of perishable goods.
- Different zones for different products (e.g., fruits, meats, dairy).
- Require precise temperature and humidity control.
- Multiple compressors and large evaporators are used.

Air Conditioning Systems

- Used for human comfort and industrial process control.
- Window ACs, Split ACs, and Centralized AC plants all rely on VCRS.
- They cool and dehumidify the air.
- Refrigerants like R22, R134a, R32, and R410A are common.

Food Processing Industry

- Crucial for freezing, chilling, and maintaining the cold chain.
- Applications include dairy, meat processing, and breweries.
- Rapid cooling is often required to prevent bacterial growth.
- VCRS provides the necessary high capacity cooling.

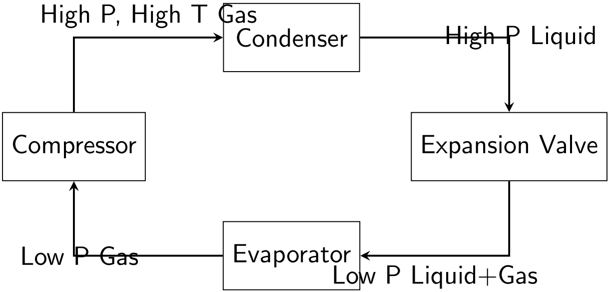
Transport Refrigeration

- Refrigerated trucks, railway cars, and marine vessels.
- Ensure perishable goods remain fresh during transit.
- Systems must be robust to withstand vibrations and varying ambient conditions.
- Often powered by the vehicle's engine or a separate diesel generator.

Industrial Applications

- Chemical and pharmaceutical industries for process cooling.
- Oil refineries for gas liquefaction and separation.
- Manufacturing processes requiring precise temperature control (e.g., plastics cooling).
- VCRS can be scaled to provide massive cooling capacities.

VCRS Schematic Diagram



Comparison of Applications

Application	Typical Temp Range	Common Refrigerant
Domestic AC	$20°C$ to $25°C$	R-32, R-410A
Domestic Fridge	$2°C$ to $5°C$ (Fridge), $-18°C$ (Freezer)	R-134a, R-600a
Ice Plant	$-10°C$ to $-5°C$	Ammonia (NH_3)
Cold Storage	Variable (e.g., $0°C$ to $-25°C$)	Ammonia, R-404A

Table: Comparison of different VCRS applications.

Summary

- VCRS is incredibly versatile, serving diverse needs from home comfort to large scale industrial processes.
- The basic cycle remains the same, but components and refrigerants vary based on application.
- Understanding the specific requirements of an application is crucial for selecting the right VCRS design.

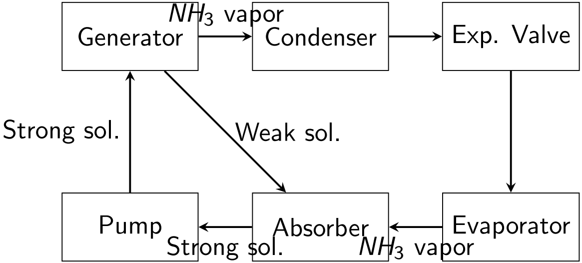
Introduction to VARS

- Vapor Absorption Refrigeration Systems (VARS) use heat energy instead of mechanical work for cooling.
- Suitable where low-grade waste heat or solar energy is available.
- Replaces the compressor of VCRS with an absorber, pump, and generator.
- Uses a refrigerant-absorbent pair (e.g., Ammonia-Water or Water-Lithium Bromide).

VARS vs VCRS

- VCRS uses high-grade energy (mechanical/electrical work).
- VARS uses low-grade energy (heat).
- VARS has fewer moving parts (only a small liquid pump), resulting in quieter operation and less wear.
- VARS typically has a lower Coefficient of Performance (COP) than VCRS.

Simple VARS Diagram



The Generator

- Heat is supplied to the generator from an external source (steam, gas flame, solar).
- The strong refrigerant-absorbent solution is heated.
- The refrigerant (having a lower boiling point) vaporizes, separating from the absorbent.
- The remaining weak solution flows back to the absorber.

The Absorber

- Receives low-pressure refrigerant vapor from the evaporator.
- The weak solution from the generator absorbs this vapor, forming a strong solution.
- Absorption is an exothermic process; heat must be rejected to cooling water.
- A strong solution is essential for the pump to move it to the generator efficiently.

Ammonia-Water System

- Ammonia (NH_3) acts as the refrigerant.
- Water (H_2O) acts as the absorbent.
- Widely used in industrial applications and large commercial systems.
- Requires an analyzer and rectifier to ensure pure ammonia vapor enters the condenser (since water can also vaporize slightly in the generator).

Analyzer and Rectifier

- **Analyzer:** A distillation column on top of the generator. It cools the rising vapors, causing water to condense and fall back, while ammonia continues.
- **Rectifier (Dephlegmator):** A water-cooled heat exchanger that further cools the vapor, condensing any remaining water vapor to ensure pure ammonia goes to the condenser.

Water-Lithium Bromide System

- Water (H_2O) acts as the refrigerant.
- Lithium Bromide ($LiBr$) acts as the absorbent.
- Used primarily for air conditioning applications (temperatures $> 0^\circ C$).
- $LiBr$ is a salt, so it does not vaporize in the generator, eliminating the need for an analyzer and rectifier.

Electrolux System (Domestic VARS)

- Also known as the three-fluid absorption system.
- Uses Ammonia (refrigerant), Water (absorbent), and Hydrogen (inert gas).
- No pump is required; circulation is driven by gravity and heat (bubble pump).
- Hydrogen lowers the partial pressure of ammonia in the evaporator, allowing it to evaporate at a low temperature while total system pressure remains uniform.

COP of VARS

The Coefficient of Performance (COP) for a VARS is given by:

$$\text{COP} = \frac{\text{Refrigerating Effect (Evaporator)}}{\text{Heat Input (Generator)} + \text{Work Input (Pump)}}$$

Since pump work is negligible compared to generator heat:

$$\text{COP} \approx \frac{Q_E}{Q_G}$$

Maximum theoretical COP:

$$\text{COP}_{\text{max}} = \left(\frac{T_E}{T_G}\right)\left(\frac{T_G - T_C}{T_C - T_E}\right)$$

Where T_E = Evaporator temp, T_G = Generator temp, T_C = Condenser/Absorber temp.

VARS vs VCRS Comparison Table

Feature	VARS	VCRS
Energy Input	Heat (Low Grade)	Mechanical Work (High Grade)
Moving Parts	Only pump (low wear)	Compressor (high wear)
Noise	Very quiet	Noisy
COP	Low (typically 0.5 - 0.8)	High (typically 2 - 5)
Part Load Perf.	Excellent	Poor

Table: Comparison between VARS and VCRS.

Advantages and Disadvantages

- **Advantages:** Uses waste heat, low noise, low maintenance, excellent part-load performance, environmentally friendly refrigerants (water, ammonia).
- **Disadvantages:** Low COP, bulky equipment, larger cooling water requirement (for absorber and condenser), ammonia is toxic (in $NH_3 - H_2O$ systems).

Introduction to Refrigerants

- A refrigerant is a substance used in a heat cycle to transfer heat from one area and remove it to another.
- Usually a fluid that undergoes a phase change from a liquid to a gas and back again.
- The choice of refrigerant significantly impacts the performance, safety, and environmental impact of the refrigeration system.

Classification of Refrigerants

- **Primary Refrigerants:** Undergo phase changes in the refrigeration cycle (e.g., R134a, Ammonia, Freon).
- **Secondary Refrigerants:** Fluids cooled by primary refrigerants and used to transport cooling to the desired space (e.g., water, brine solutions).

Types of Primary Refrigerants

- **Halocarbons:** Contain Halogens (Chlorine, Fluorine). e.g., CFCs (R11, R12), HCFCs (R22), HFCs (R134a, R32).
- **Hydrocarbons (HCs):** e.g., Methane, Ethane, Propane (R290), Isobutane (R600a).
- **Inorganic Compounds:** e.g., Ammonia (NH_3 - R717), Water (H_2O - R718), Carbon Dioxide (CO_2 - R744).
- **Azeotropic Mixtures:** Mixtures that behave as a single pure substance (e.g., R502).

Desirable Properties: Thermodynamic

- **Low Boiling Point:** Allows operation at positive pressures even at low temperatures.
- **High Critical Temperature:** Condensation should occur well below the critical point for efficient heat rejection.
- **High Latent Heat of Vaporization:** Maximizes refrigerating effect per kg of refrigerant, reducing required mass flow rate.
- **Low Specific Volume of Vapor:** Reduces the required size of the compressor.

Desirable Properties: Chemical & Physical

- **Non-toxic and Non-flammable:** Crucial for safety.
- **Chemically Stable:** Should not decompose at operating temperatures.
- **Non-corrosive:** Should not react with system materials (metals, seals, oils).
- **High Thermal Conductivity:** Improves heat transfer in evaporator and condenser.
- **Miscibility with Oil:** Should mix well with compressor oil to ensure oil return to the compressor.

Environmental Impact: ODP and GWP

- **Ozone Depletion Potential (ODP):** Measure of a substance's ability to destroy stratospheric ozone relative to CFC-11 (ODP = 1.0).
- **Global Warming Potential (GWP):** Measure of how much heat a greenhouse gas traps in the atmosphere relative to CO2 (GWP = 1.0).
- Modern regulations (Montreal and Kigali Protocols) mandate phasing out refrigerants with high ODP and GWP.

Refrigerant Nomenclature (Halocarbons)

Refrigerants are designated by 'R' followed by a number based on their chemical formula: $C_m H_n F_p Cl_q$ The number is derived as:
$R(m-1)(n+1)(p)$

- First digit (if not zero) = number of Carbon atoms minus 1
- Second digit = number of Hydrogen atoms plus 1
- Third digit = number of Fluorine atoms

Example: Dichlorodifluoromethane (CCl_2F_2) m=1, n=0, p=2, q=2
Number = R(1-1)(0+1)(2) = R012 → **R12**

Refrigerant Nomenclature (Inorganic)

- Inorganic refrigerants are designated by adding 700 to their molecular weight.
- Examples:
- Ammonia (NH_3): Molecular weight $= 17 \rightarrow$ **R717**
- Water (H_2O): Molecular weight $= 18 \rightarrow$ **R718**
- Carbon Dioxide (CO_2): Molecular weight $= 44 \rightarrow$ **R744**

Common Refrigerants and Applications

Refrigerant	Type	Typical Application
R-134a	HFC	Domestic fridges, Car AC
R-410A	HFC Blend	Residential and commercial AC
R-32	HFC	Modern residential AC (lower GWP)
R-600a (Isobutane)	HC	Modern domestic fridges
R-717 (Ammonia)	Inorganic	Large industrial cold storage

Table: Common refrigerants and their uses.

The Shift to Natural Refrigerants

- Due to high GWP of HFCs, there is a push towards 'natural' refrigerants.
- These include Ammonia, CO_2, and Hydrocarbons.
- They have zero ODP and near-zero GWP.
- Challenges include flammability (Hydrocarbons), toxicity (Ammonia), and high operating pressures (CO_2).

Refrigerant Selection Criteria

- Selection is a compromise between competing requirements.
- Considerations include:
- 1. Operating temperatures (evaporator and condenser)
- 2. Cooling capacity required
- 3. Safety constraints (toxicity, flammability)
- 4. Environmental regulations
- 5. Cost and availability

Summary

- Refrigerants are the lifeblood of refrigeration systems.
- Their thermodynamic, chemical, and physical properties dictate system design.
- Environmental concerns (ODP, GWP) are driving the industry towards sustainable alternatives like HFOs and natural refrigerants.

Introduction to Air Conditioning

- Air conditioning is the process of altering the properties of air.
- Primarily used to create more comfortable interior conditions for humans.
- Also used in industrial environments to ensure optimal conditions for processes or equipment.
- Key parameters controlled: Temperature, Humidity, Cleanliness, and Air Motion.

Need for Air Conditioning

- **Human Comfort:** To maintain body temperature within comfortable limits and remove perspiration.
- **Industrial Processes:** Precise control for manufacturing (e.g., textiles, pharmaceuticals, electronics).
- **Food Preservation:** Maintaining specific humidity and temperature for long-term storage.
- **Equipment Cooling:** Datacenters and server rooms require strict environmental control to prevent overheating.

Types of Air Conditioning Systems

- **Summer Air Conditioning:** Cools and dehumidifies the air.
- **Winter Air Conditioning:** Heats and humidifies the air.
- **Year-round Air Conditioning:** Combines both capabilities to provide comfort regardless of outside weather.

Comfort vs. Industrial Air Conditioning

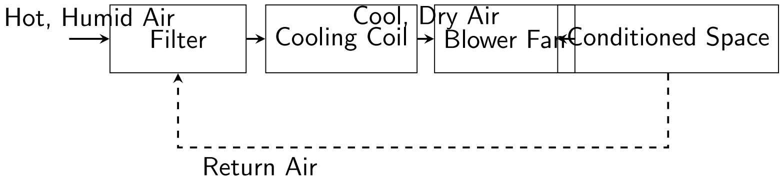
Comfort AC	**Industrial AC**
Focuses on human comfort.	Focuses on process requirements.
Typical conditions: $22-26^{\circ}C$, 40-60% RH.	Conditions vary widely based on process.
Air purity is important but not extreme.	May require ultra-clean rooms (e.g., semiconductors).

Table: Comfort vs Industrial AC

Basic Components of an AC System

- **Cooling/Heating Source:** Chiller, direct expansion coil, boiler, or furnace.
- **Air Handling Unit (AHU):** Contains fans, filters, heating/cooling coils.
- **Distribution System:** Ductwork to deliver conditioned air and return room air.
- **Control System:** Thermostats and sensors to regulate temperature and humidity.

Summer Air Conditioning System



Winter Air Conditioning System

- Outside air in winter is typically cold and dry.
- The system must heat the air and add moisture (humidification).
- Key components added: Heating coil (steam, hot water, or electric) and a humidifier (steam injection or water spray).
- Important for preventing dry skin and static electricity during winter.

Year-Round Air Conditioning System

- Contains equipment for both summer and winter operation.
- Includes pre-heating coils, cooling/dehumidifying coils, humidifiers, and reheat coils.
- A sophisticated control system switches modes based on sensory input and setpoints.
- Ensures continuous comfort throughout all seasons.

Air Distribution Systems

- **All-Air Systems:** Only air is delivered to the rooms (e.g., VAV systems).
- **All-Water Systems:** Chilled or hot water is piped to fan coil units in the rooms.
- **Air-Water Systems:** Combines both, providing primary ventilation air and using water for major heating/cooling loads.
- **Direct Expansion (DX) Systems:** Refrigerant expands directly in coils located in the air stream (e.g., split ACs).

Importance of Ventilation

- Air conditioning isn't just about temperature; it's also about indoor air quality (IAQ).
- Adequate outside air must be introduced to dilute pollutants and CO_2.
- Filters must remove dust, pollen, and other particulate matter.
- Poor ventilation can lead to 'Sick Building Syndrome'.

Energy Efficiency in AC

- AC systems are major energy consumers.
- Efficiency is measured by EER (Energy Efficiency Ratio) or SEER (Seasonal EER) for cooling, and COP for heating.
- Strategies to improve efficiency: Variable Speed Drives (VFDs), Economizers (using outside cool air), Heat Recovery systems, and proper insulation.

Summary

- Air conditioning involves simultaneous control of temperature, humidity, purity, and air motion.
- Systems are tailored for summer, winter, or year-round operation.
- The choice between comfort and industrial AC dictates the stringency of the control parameters.
- Modern AC design emphasizes energy efficiency and Indoor Air Quality.

Introduction to Air Properties

- Air conditioning involves manipulating air to achieve desired conditions.
- To do this effectively, we must understand the physical and thermodynamic properties of air.
- The study of these properties, specifically mixtures of dry air and water vapor, is called Psychrometrics.

Composition of Dry Air

- Dry air is a mechanical mixture of gases.
- Main components by volume (approximate):
- Nitrogen (N_2): 78.09%
- Oxygen (O_2): 20.95%
- Argon (Ar): 0.93%
- Carbon Dioxide (CO_2): 0.03%
- Molecular weight of dry air $\approx$ 28.966 kg/kmol.

Moist Air

- Atmospheric air is never completely dry; it always contains some water vapor.
- Moist air is treated as a mixture of two ideal gases: dry air and water vapor.
- The amount of water vapor can vary from zero (dry air) to a maximum (saturated air).
- The behavior of moist air is fundamental to AC calculations.

Dalton's Law of Partial Pressures

The total pressure of a gas mixture is the sum of the partial pressures of the individual gases. For moist air:

$$p = p_a + p_v$$

Where:

- p = Total atmospheric (barometric) pressure
- p_a = Partial pressure of dry air
- p_v = Partial pressure of water vapor

Specific Humidity (Humidity Ratio)

Specific Humidity (W or ω) is the mass of water vapor per unit mass of dry air.

$$W = \frac{m_v}{m_a}$$

Using ideal gas laws ($pV = mRT$):

$$W = \frac{\frac{p_v V}{R_v T}}{\frac{p_a V}{R_a T}} = \frac{R_a}{R_v} \cdot \frac{p_v}{p_a}$$

Given $R_a = 0.287$ kJ/kg·K and $R_v = 0.461$ kJ/kg·K:

$$W = 0.622 \frac{p_v}{p - p_v} \text{ (kg of vapor / kg of dry air)}$$

Relative Humidity (RH or ϕ)

Relative Humidity (ϕ) is the ratio of the actual mass of water vapor in a given volume to the maximum mass of water vapor that volume could hold at the same temperature.

$$\phi = \frac{m_v}{m_s} = \frac{p_v}{p_s}$$

Where:

- p_v = Actual partial pressure of water vapor
- p_s = Saturation pressure of water vapor at the same dry bulb temperature

Expressed as a percentage. 100% RH means saturated air.

Degree of Saturation (μ)

Degree of Saturation (μ) is the ratio of actual specific humidity to the specific humidity of saturated air at the same temperature.

$$\mu = \frac{W}{W_s}$$

Relationship between μ and ϕ:

$$\mu = \phi \left(\frac{p - p_s}{p - p_v} \right)$$

For normal air conditioning conditions, $\mu \approx \phi$ (when expressed as fractions).

Important Temperatures in Psychrometrics

- **Dry Bulb Temperature (DBT):** The temperature recorded by an ordinary thermometer exposed to the air. Indicates sensible heat.
- **Wet Bulb Temperature (WBT):** The temperature recorded by a thermometer whose bulb is covered by a water-wetted wick exposed to a moving air stream. Indicates the lowest temperature attainable by evaporative cooling.
- **Dew Point Temperature (DPT):** The temperature at which water vapor in the air starts condensing when cooled at constant pressure. (Saturation temperature corresponding to p_v).

Enthalpy of Moist Air (h)

The total enthalpy of moist air is the sum of the enthalpy of dry air and the enthalpy of water vapor. Expressed per kg of dry air:

$$h = h_a + W \cdot h_v$$

$$h = C_{pa} \cdot t + W(h_{fg} + C_{pv} \cdot t)$$

Approximate practical formula:

$$h \approx 1.005t + W(2500 + 1.88t) \text{ kJ/kg of dry air}$$

Where t is the DBT in $^\circ C$.

Specific Volume (v)

Specific Volume (v) is the volume occupied by the mixture per kg of dry air. Using the ideal gas equation for the dry air component:

$$p_a V = m_a R_a T$$

$$v = \frac{V}{m_a} = \frac{R_a T}{p_a} = \frac{R_a T}{p - p_v}$$

Where T is absolute temperature (K). Unit: m^3/kg of dry air.

Relationship between Temperatures

- For unsaturated air (RH ¡ 100%): DBT ¿ WBT ¿ DPT.
- As air becomes more humid, WBT approaches DBT.
- For saturated air (RH = 100%): DBT = WBT = DPT.
- The difference (DBT - WBT) is called the Wet Bulb Depression.
- The difference (DBT - DPT) is called the Dew Point Depression.

Summary

- Air properties are defined by relationships between dry air and water vapor.
- Key parameters include Specific Humidity, Relative Humidity, DBT, WBT, DPT, and Enthalpy.
- Dalton's Law of partial pressures and ideal gas laws form the foundation for psychrometric calculations.
- Understanding these properties is essential for analyzing air conditioning processes.

Introduction to Psychrometrics

- Psychrometrics is the science dealing with the thermodynamic properties of moist air.
- It involves the study of air-water vapor mixtures.
- Essential for designing and analyzing air conditioning, ventilation, and heating systems.
- The psychrometric chart is a graphical representation of these properties.

The Psychrometric Chart

- A complex graph containing curves and lines representing the properties of moist air at a constant barometric pressure (usually sea level).
- Allows quick determination of properties without complex calculations.
- Knowing any TWO independent properties fixes the state point on the chart.
- From that point, all other properties can be read directly.

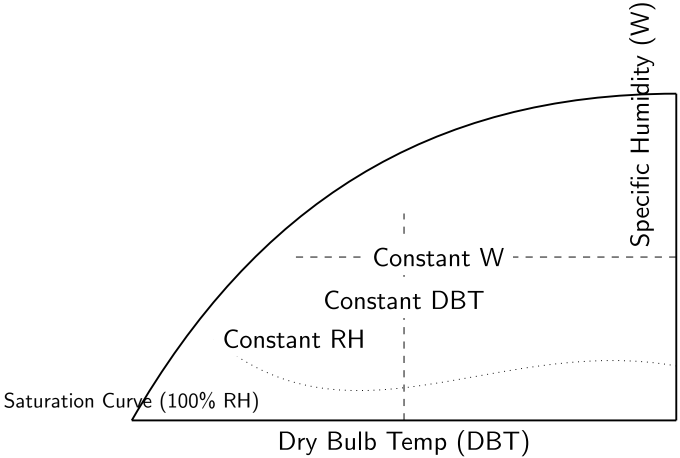
Basic Lines on the Chart (1)

- **Dry Bulb Temperature (DBT) Lines:** Vertical lines. DBT increases from left to right.
- **Specific Humidity (W) Lines:** Horizontal lines. W increases from bottom to top.
- **Relative Humidity (RH) Curves:** Curved lines sweeping upwards from bottom-left to top-right. The leftmost curve is the Saturation Curve (100% RH).

Basic Lines on the Chart (2)

- **Wet Bulb Temperature (WBT) Lines:** Straight lines sloping diagonally downwards from left to right. They intersect the saturation curve at the corresponding DBT.
- **Dew Point Temperature (DPT) Lines:** Read by moving horizontally to the left from the state point to the saturation curve.
- **Enthalpy Lines:** Straight lines sloping downwards from left to right, nearly parallel to WBT lines. Read on scales located outside the main chart body.
- **Specific Volume Lines:** Straight lines sloping steeply downwards from left to right.

Visualizing the Chart Structure



Psychrometric Processes

- Changes in the state of air are called psychrometric processes.
- They can be represented as lines or vectors on the psychrometric chart.
- Major processes:
- 1. Sensible Heating and Cooling
- 2. Humidification and Dehumidification
- 3. Cooling and Dehumidification
- 4. Heating and Humidification

Sensible Heating and Cooling

- **Sensible Heating:** Adding heat without changing moisture content. State point moves horizontally to the right. DBT increases, W is constant, RH decreases.
- **Sensible Cooling:** Removing heat without changing moisture content. State point moves horizontally to the left. DBT decreases, W is constant, RH increases.
- Requires heat exchangers (heating/cooling coils) operating above the air's Dew Point.

Humidification and Dehumidification

- **Humidification:** Adding moisture without changing DBT. State point moves vertically upwards. W increases, RH increases.
- **Dehumidification:** Removing moisture without changing DBT. State point moves vertically downwards. (Pure dehumidification is difficult in practice).
- Typically achieved using steam injection (heating+humidification) or chemical desiccants (heating+dehumidification).

Cooling and Dehumidification

Most common summer AC process. Air passes over a cooling coil with a surface temperature below the air's Dew Point. Air cools sensibly until it hits the DPT, then water vapor condenses. State point moves down and to the left. **Apparatus Dew Point (ADP):** The effective surface temperature of the cooling coil. **Bypass Factor (BPF):** Fraction of air that passes through the coil unaffected.

$$BPF = \frac{t_2 - t_{adp}}{t_1 - t_{adp}}$$

Heating and Humidification

- Most common winter AC process.
- Air is heated and moisture is added to combat dry winter conditions.
- State point moves up and to the right.
- Can be achieved by passing air through a heated water spray or by separate heating coils and steam humidifiers.

Adiabatic Mixing of Air Streams

Common in AC when return air mixes with fresh outside air. The state of the mixed air lies on a straight line connecting the two initial states on the chart. The position depends on the mass flow rates (m_1 and m_2):

$$\frac{\text{Distance } 1-3}{\text{Distance } 2-3} = \frac{m_2}{m_1}$$

Properties of mixed state (3):

$$h_3 = \frac{m_1 h_1 + m_2 h_2}{m_1 + m_2}$$

$$W_3 = \frac{m_1 W_1 + m_2 W_2}{m_1 + m_2}$$

Summary

- The psychrometric chart is an invaluable tool for visualizing and solving AC problems.
- It relates key properties: DBT, WBT, W, RH, Enthalpy, and Specific Volume.
- Various AC processes (heating, cooling, humidifying, mixing) can be plotted to determine energy and mass transfer requirements.
- Mastery of the chart is essential for HVAC engineers.

Introduction to Numerical Examples

- In this lecture, we apply the principles of psychrometrics to solve practical problems.
- We will use formulas and the psychrometric chart to find unknown properties and determine heat/moisture loads.
- Familiarity with interpreting the chart is crucial for these exercises.

Problem 1: Determining Properties

Given: Air at $30^\circ C$ DBT and 60% RH. Barometric pressure is 1 atm (1.013 bar). **Find:** Specific humidity (W), Enthalpy (h), DPT, and WBT.
Solution (Analytical): From Steam Tables at $30^\circ C$: $p_s = 0.0424$ bar.
Calculate p_v: $p_v = \phi \cdot p_s = 0.60 \cdot 0.0424 = 0.0254$ bar. Calculate W:
$W = 0.622 \frac{p_v}{p - p_v} = 0.622 \frac{0.0254}{1.013 - 0.0254} = 0.016$ kg/kg da

Problem 1: Solution Continued

Calculate Enthalpy (h):

$$h = 1.005t + W(2500 + 1.88t)$$

$$h = 1.005(30) + 0.016(2500 + 1.88(30))$$

$$h = 30.15 + 0.016(2556.4) = 71.05 \text{ kJ/kg da}$$

Solution (Using Chart): Locate intersection of $30^\circ C$ vertical line and 60% RH curve. Read horizontally to right: $W \approx 16$ g/kg da. Follow enthalpy line: $h \approx 71$ kJ/kg da. Read horizontally left to saturation curve: $DPT \approx 21.4^\circ C$. Follow WBT line to saturation curve: $WBT \approx 23.8^\circ C$.

Problem 2: Sensible Heating

Given: 1000 m^3/h of air at $15^\circ C$ DBT and $10^\circ C$ WBT is heated to $25^\circ C$ DBT. **Find:** Heat added (kW) and final RH. **Solution (via Chart):** State 1: $15^\circ C$ DBT, $10^\circ C$ WBT. From chart: $h_1 \approx 29$ kJ/kg, $v_1 \approx 0.82$ m^3/kg, $RH_1 \approx 50\%$. Mass flow rate: $\dot{m} = \frac{\dot{V}}{v_1} = \frac{1000/3600}{0.82} = 0.339$ kg/s. Process is sensible heating (horizontal line to right) to $25^\circ C$.

Problem 2: Solution Continued

State 2: $25^\circ C$ DBT, same Specific Humidity as State 1. From chart at State 2: $h_2 \approx 39.5$ kJ/kg, $RH_2 \approx 26\%$. Heat added (Q):

$$Q = \dot{m}(h_2 - h_1)$$

$$Q = 0.339 \text{ kg/s} \cdot (39.5 - 29) \text{ kJ/kg}$$

$$Q = 3.56 \text{ kW}$$

Conclusion: The heater must supply 3.56 kW, and the room will feel quite dry (26% RH).

Problem 3: Cooling and Dehumidification

Given: Air enters a cooling coil at $32^{\circ}C$ DBT, $24^{\circ}C$ WBT. It leaves at $20^{\circ}C$ DBT, $18^{\circ}C$ WBT. Mass flow rate is 1.5 kg/s. **Find:** Total cooling capacity required and amount of water condensed. **Solution:** From chart for State 1 ($32^{\circ}C$ DBT, $24^{\circ}C$ WBT): $h_1 = 72$ kJ/kg, $W_1 = 15.5$ g/kg. From chart for State 2 ($20^{\circ}C$ DBT, $18^{\circ}C$ WBT): $h_2 = 51$ kJ/kg, $W_2 = 11.5$ g/kg.

Problem 3: Solution Continued

Total Cooling Capacity (Required Load):

$$Q_{\text{total}} = \dot{m}(h_1 - h_2)$$

$$Q_{\text{total}} = 1.5 \cdot (72 - 51) = 31.5 \text{ kW}$$

To convert to Tons of Refrigeration (TR): $31.5/3.517 \approx 9.0$ TR. **Rate of Condensation (Moisture Removed):**

$$\dot{m}_w = \dot{m}(W_1 - W_2)$$

$$\dot{m}_w = 1.5 \cdot (0.0155 - 0.0115) = 0.006 \text{ kg/s}$$

Or $0.006 \cdot 3600 = 21.6$ kg/hour (liters/hour).

Problem 4: Mixing of Air Streams

Given: Stream 1 (Return Air): $26^{\circ}C$ DBT, 50% RH, $\dot{m}_1 = 2$ kg/s. Stream 2 (Fresh Air): $35^{\circ}C$ DBT, $28^{\circ}C$ WBT, $\dot{m}_2 = 1$ kg/s. **Find:** Enthalpy and DBT of the mixed air. **Solution:** State 1: From chart, $h_1 \approx 53$ kJ/kg. State 2: From chart, $h_2 \approx 90$ kJ/kg.

Problem 4: Solution Continued

Calculate mixed enthalpy (h_3):

$$h_3 = \frac{\dot{m}_1 h_1 + \dot{m}_2 h_2}{\dot{m}_1 + \dot{m}_2}$$

$$h_3 = \frac{2(53) + 1(90)}{2 + 1} = \frac{196}{3} = 65.33 \text{ kJ/kg}$$

Calculate mixed DBT (t_3) using approximate linear relationship:

$$t_3 = \frac{\dot{m}_1 t_1 + \dot{m}_2 t_2}{\dot{m}_1 + \dot{m}_2} = \frac{2(26) + 1(35)}{3} = \frac{87}{3} = 29^\circ C$$

State 3 can now be plotted on the chart at the intersection of $h = 65.33$ and $DBT = 29^\circ C$.

Understanding Bypass Factor (BPF)

Not all air touches the cooling coil surface. BPF represents the fraction of air that "bypasses" the coil unchanged. If t_1 is inlet air DBT, t_2 is outlet air DBT, and t_{adp} is apparatus dew point (coil surface temp):

$$BPF = \frac{t_2 - t_{adp}}{t_1 - t_{adp}}$$

A lower BPF means a more efficient coil (more rows, closer fins), but increases air pressure drop.

Sensible Heat Factor (SHF)

Cooling loads consist of Sensible Heat (changes temperature) and Latent Heat (changes moisture). Total Heat (Q_T) = Sensible Heat (Q_S) + Latent Heat (Q_L)

$$SHF = \frac{Q_S}{Q_T} = \frac{Q_S}{Q_S + Q_L}$$

On the psychrometric chart, SHF determines the slope of the process line for the room. A low SHF (e.g., 0.6) indicates a high moisture load (e.g., crowded theater). A high SHF (e.g., 0.9) indicates mostly sensible load (e.g., computer room).

Summary of Problem Solving

- Always start by clearly defining the states on the psychrometric chart.
- Use mass flow rate (kg/s of dry air), not volume flow rate, for energy balances.
- Remember the fundamental equations: $Q = \dot{m}\Delta h$ and Moisture Removed $= \dot{m}\Delta W$.
- Accuracy depends on careful reading of the psychrometric chart or using precise thermodynamic software.

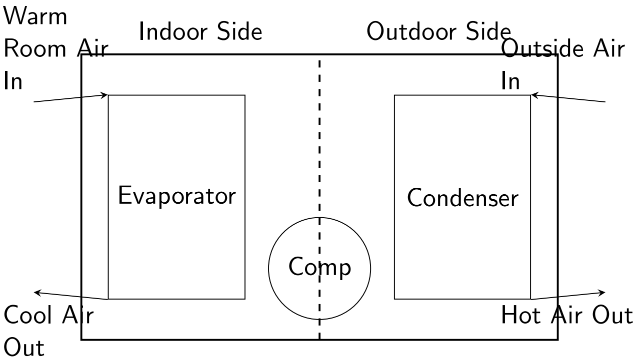
Introduction to Air Conditioners

- An air conditioner is a device that alters the properties of air (temperature, humidity) to provide comfort or meet specific requirements.
- Typically utilizes the Vapor Compression Refrigeration System (VCRS).
- Categorized based on size, application, and physical configuration.
- Common types: Window, Split, Packaged, and Centralized systems.

Window Air Conditioner

- A self-contained unit usually installed in a window or a hole in the wall.
- Contains all components (compressor, condenser, expansion valve, evaporator) in a single casing.
- Suitable for small single rooms.
- Capacities typically range from 0.5 TR to 2.5 TR.

Window AC Layout



Working of Window AC

- A single double-shaft motor drives two fans.
- The indoor blower fan draws room air over the cold evaporator coil, cooling and dehumidifying it.
- The outdoor propeller fan draws outside air over the hot condenser coil to reject heat.
- Condensate water from the evaporator often drips onto the condenser to improve cooling efficiency.

Split Air Conditioner

- Divided into two separate units: Indoor Unit (IDU) and Outdoor Unit (ODU).
- **IDU:** Contains the evaporator coil, expansion valve (often), and a quiet blower fan. Installed inside the room.
- **ODU:** Contains the noisy compressor, condenser coil, and condenser fan. Installed outside.
- Connected by copper tubing carrying refrigerant.

Advantages of Split AC over Window AC

- **Quieter Operation:** The noisy compressor is located outside.
- **Aesthetics:** No need to block a window; IDU designs are sleek and mount on walls or ceilings.
- **Flexibility:** ODU can be placed far from the IDU.
- **Capacity:** Available in higher capacities than window units.

Inverter Technology in ACs

- Traditional ACs have fixed-speed compressors (ON/OFF control).
- Inverter ACs have variable-speed compressors.
- They adjust compressor speed based on the cooling load.
- Benefits: Better temperature control, higher energy efficiency (less power surges), and quieter operation.

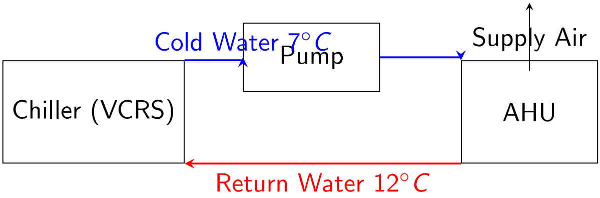
Packaged Air Conditioners

- Used for larger spaces like restaurants, small halls, or offices (3 TR to 15 TR).
- All components are enclosed in a single large casing.
- Similar to window units but much larger.
- The cooled air is usually distributed through a ducting system to different parts of the space.

Centralized Air Conditioning

- Used for large buildings, malls, airports, and hospitals.
- Usually involves a large Chiller Plant.
- The chiller cools water, which is then pumped through pipes to Air Handling Units (AHUs) or Fan Coil Units (FCUs) throughout the building.
- AHUs blow air over the chilled water coils to cool the spaces.

Chilled Water System Schematic



Cooling Towers

- In large centralized systems, water-cooled condensers are used instead of air-cooled.
- Heat from the condenser is transferred to cooling water.
- This warm cooling water is sent to a Cooling Tower outside the building.
- The cooling tower uses evaporation to cool the water back down before returning it to the condenser.

Summary

- Air conditioners range from small window units to massive centralized chiller plants.
- Window and split ACs are common for domestic use.
- Packaged and Centralized systems are used for commercial and industrial applications.
- Advancements like Inverter technology are significantly improving energy efficiency.

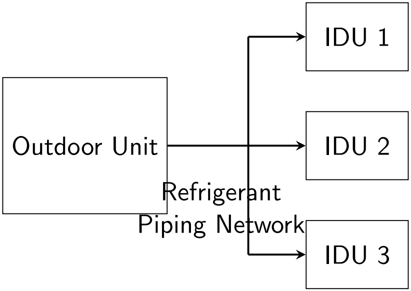
Advanced Air Conditioning Concepts

- Building on the previous lecture, we delve into more complex AC systems and components.
- Focus on variable flow systems, heat recovery, and indoor air quality management.
- These technologies are essential for modern, energy-efficient building design.

Variable Refrigerant Flow (VRF) Systems

- Advanced split system where one outdoor unit serves multiple indoor units.
- Refrigerant flow is varied dynamically to match the exact cooling/heating demand of each zone.
- Uses inverter-driven compressors.
- Highly efficient, provides independent zoning control, and requires less ductwork.

VRF Schematic



Variable Air Volume (VAV) Systems

- Common in large commercial buildings with centralized AHUs.
- Instead of maintaining a constant air flow and varying the temperature, VAV maintains a constant supply air temperature and varies the volume of air.
- VAV boxes in the ductwork use dampers to restrict airflow as the room cooling load decreases.
- Saves significant fan energy at partial loads.

Heat Recovery Systems

- Buildings require fresh outdoor air, which must be cooled/heated, expending energy.
- Simultaneously, conditioned indoor air is exhausted to the outside.
- Heat recovery devices transfer heat (and sometimes moisture) between the exhaust air and the fresh intake air.
- Reduces the load on the heating and cooling coils.

Types of Heat Recovery

- **Sensible Heat Recovery:** Transfers only sensible heat (temperature). e.g., Run-around coils, Plate heat exchangers.
- **Total (Enthalpy) Heat Recovery:** Transfers both sensible and latent heat (moisture). e.g., Thermal Wheels (Rotary enthalpy wheels).
- Enthalpy wheels are very effective in humid climates where reducing moisture load of incoming air is crucial.

Air Filters and Indoor Air Quality (IAQ)

- AC systems must remove particulates to protect equipment and ensure healthy IAQ.
- **Pre-filters:** Catch large dust particles, protecting finer filters.
- **Bag/Pocket filters:** Medium efficiency, used in standard commercial AHUs.
- **HEPA (High Efficiency Particulate Air) filters:** Remove 99.97% of particles $\geq 0.3\mu m$. Used in hospitals and clean rooms.

Dehumidification Methods

- **Cooling-based Dehumidification:** Cooling air below its dew point (standard AC process).
- **Desiccant Dehumidification:** Passing air through a material (desiccant like silica gel) that absorbs moisture.
- Desiccant systems are used when very low humidity is required, which would cause coils to freeze in a standard system.

Smart AC Controls

- Modern systems rely on Building Management Systems (BMS).
- Use sensors (temperature, humidity, occupancy, CO_2) to optimize operation.
- Features include programmable scheduling, remote monitoring, and fault detection.
- Smart controls are critical for maximizing energy efficiency in large buildings.

Evaporative Coolers (Desert Coolers)

- An alternative to VCRS in hot, dry climates.
- Works by passing hot, dry outside air over water-soaked pads.
- Water evaporates, absorbing sensible heat from the air (adiabatic cooling).
- Air DBT decreases, but humidity increases. Only effective if outside air is very dry.

Comparison: Evaporative vs. VCRS AC

Feature	Evaporative Cooler	VCRS AC
Energy Use	Very Low (Fan + small pump)	High (Compressor)
Climate Suitability	Hot and Dry	Any climate
Humidity Control	Adds humidity	Removes humidity
Temperature	Dependent on wet-bulb temp	Precise control

Summary

- Advanced AC technologies focus on efficiency and precise control.
- VRF and VAV systems optimize energy use by matching capacity to demand.
- Heat recovery and proper filtration are essential for sustainable and healthy building environments.
- The choice of system depends heavily on building size, climate, and specific application requirements.

Lecture 4.37

Air Conditioner: Troubleshooting & Heat Load

Agenda

- Heat Load Sources
- Sensible vs Latent Heat
- Cooling Load Calculation
- Common AC Problems
- Troubleshooting Chart
- Conclusion

Heat Load Sources

- Solar radiation through windows.
- Heat conduction through walls and roof.
- Internal heat generation (people, lights, appliances).
- Infiltration of outside air.

Sensible vs Latent Heat

- Sensible Heat: Causes a change in temperature (e.g., heat from walls, electronics).
- Latent Heat: Causes a change in humidity without temperature change (e.g., human respiration, cooking).
- Total Cooling Load = Sensible Load + Latent Load.

Heat Load Estimation Table

Source	Sensible Heat	Latent Heat
Walls/Roof	High	None
Occupants	Medium	High
Appliances	High	Low
Ventilation	Medium	Medium

Table: Heat Load Components

Cooling Load Calculation

- Formula: Q = U \times A \times \Delta T
- Where U is the overall heat transfer coefficient.
- A is the area of the wall/window.
- \Delta T is the temperature difference.

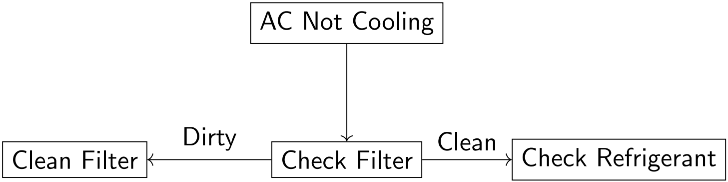
Common AC Problems

- AC not cooling sufficiently.
- Water leaking from the indoor unit.
- Unusual noises.
- Compressor not starting.

Troubleshooting: Not Cooling

- Possible causes: Dirty air filter, low refrigerant, blocked condenser.
- Solutions: Clean filter, check for leaks and recharge, clean outdoor unit.

Troubleshooting Flowchart



Troubleshooting: Water Leaks

- Usually caused by a clogged condensate drain line.
- Can also be due to a frozen evaporator coil melting.
- Solution: Clear the drain line with a vacuum or wire.

Preventive Maintenance

- Regular cleaning of filters and coils.
- Checking electrical connections.
- Lubricating moving parts.
- Inspecting ductwork for leaks.

Summary

- Accurate heat load calculation is vital for AC sizing.
- Sensible and latent heat both contribute to total load.
- Most AC problems can be resolved with basic troubleshooting and regular maintenance.

Lecture 5.38

Hydrogen Technology: Concept

Agenda

- Introduction to Hydrogen
- Why Hydrogen?
- Properties of Hydrogen
- Hydrogen as an Energy Carrier
- Applications
- Summary

Introduction to Hydrogen

- Most abundant element in the universe.
- Lightest gas, highly flammable.
- Rarely found in its pure form on Earth.
- Must be extracted from water or hydrocarbons.

Why Hydrogen?

- High energy content per unit mass.
- Clean burning (produces only water when combusted).
- Can help in decarbonizing various sectors.
- Versatile in applications (fuel cells, combustion).

Properties of Hydrogen

Property	Value
Density (at STP)	0.08988 g/L
Boiling Point	-252.87 °C
Melting Point	-259.14 °C
Energy Density (Mass)	120 MJ/kg

Table: Physical Properties of Hydrogen

Hydrogen as an Energy Carrier

- It is not an energy source, but a carrier.
- Requires energy to produce.
- Can store energy from renewable sources.
- Transports energy to where it is needed.

Hydrogen Production Concept

Colors of Hydrogen

- Grey Hydrogen: Produced from natural gas (emits CO2).
- Blue Hydrogen: From natural gas with carbon capture.
- Green Hydrogen: From renewable electricity via electrolysis.

Challenges

- High cost of production.
- Storage difficulties due to low density.
- Lack of infrastructure.
- Safety concerns (highly flammable).

Applications

- Transportation (Fuel Cell Vehicles).
- Power generation.
- Industrial processes (ammonia production, refining).
- Heating.

Future Potential

- Key to achieving net-zero emissions.
- Scalable energy storage solution.
- Global hydrogen economy development.

Summary

- Hydrogen is a versatile and clean energy carrier.
- It has a very high energy density by mass.
- Production methods determine its environmental impact.

Lecture 5.39

Green Hydrogen & Storage Forms

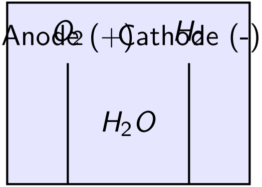
Agenda

- What is Green Hydrogen?
- Production Principles
- Why Liquid Hydrogen?
- Compressed Hydrogen
- Comparison of Storage Methods

What is Green Hydrogen?

- Hydrogen produced without greenhouse gas emissions.
- Utilizes electricity from renewable sources (solar, wind).
- Water electrolysis separates H2 and O2.
- The ultimate clean fuel.

Electrolysis Process



Importance of Green Hydrogen

- Essential for hard-to-abate sectors (steel, heavy transport).
- Allows long-term seasonal energy storage.
- Reduces dependency on fossil fuels.

The Storage Challenge

- Hydrogen has high energy per mass but low energy per volume.
- Requires significant compression or liquefaction to be useful.
- Storage methods: Compressed Gas, Liquid, Solid State.

Compressed Hydrogen

- Stored at high pressures: 350 bar to 700 bar.
- Used mainly in fuel cell vehicles.
- Requires strong tanks (carbon fiber reinforced).
- Relatively simple but bulky.

Liquid Hydrogen

- Stored at cryogenic temperatures (-253 °C).
- Higher volumetric energy density than compressed H_2.
- Requires advanced insulation (vacuum jackets).
- Boil-off is a major issue.

Storage Comparison

Feature	**Compressed H2**	**Liquid H2**
Pressure	350-700 bar	1 bar
Temperature	Ambient	-253 °C
Density	40 kg/m^3	71 kg/m^3
Energy Cost	10%	30%

Table: Compressed vs Liquid Hydrogen

Applications of Storage Types

- Compressed: Passenger cars, buses, short-range transport.
- Liquid: Aerospace, maritime shipping, large scale transport.

Safety in Storage

- High pressure risks.
- Cryogenic burns from liquid H2.
- Leakage detection is critical as H2 is odorless and colorless.

Summary

- Green hydrogen is vital for a sustainable future.
- Storage is the main technical bottleneck.
- Choice between compressed and liquid depends on application scale and duration.

Lecture 5.40

Hydrogen Production Methods

Agenda

- Overview of Production
- Steam Methane Reforming (SMR)
- Coal Gasification
- Biomass Gasification
- Comparison of Methods
- Environmental Impact

Overview of Production

- Hydrogen must be extracted from compounds (water, hydrocarbons).
- Currently, 95% of hydrogen is produced from fossil fuels.
- Primary methods: Thermochemical, Electrolytic, Biological.

Steam Methane Reforming (SMR)

- Most common and cost-effective method (Grey Hydrogen).
- Reacts methane with high-temperature steam.
- Produces synthesis gas (syngas), a mixture of H2 and CO.
- Requires catalyst and high temperatures (700-1000 C).

SMR Chemical Reactions

- **Reforming:** $CH_4 + H_2O \rightleftharpoons CO + 3H_2$ (Endothermic)
- **Water-Gas Shift:** $CO + H_2O \rightleftharpoons CO_2 + H_2$ (Exothermic)

Coal Gasification

- Reacts coal with oxygen and steam under high pressure and temperature.
- Forms syngas, followed by a water-gas shift reaction.
- Highly carbon-intensive unless Carbon Capture and Storage (CCS) is used (Brown/Black Hydrogen).

Gasification Schematic

Biomass Gasification

- Similar to coal gasification but uses renewable biomass.
- Can be carbon neutral if biomass is sustainably sourced.
- Lower efficiency compared to fossil fuel methods.

Comparison of Methods

Method	Cost	Emissions
SMR	Low	High
Coal Gas.	Low/Med	Very High
Biomass Gas.	Medium	Neutral
Electrolysis	High	Zero

Table: Production Method Comparison

Environmental Impact

- Fossil fuel methods release substantial CO2.
- The shift towards Blue Hydrogen (SMR + CCS) and Green Hydrogen is essential.
- Economics vs Environment.

Carbon Capture & Storage (CCS)

- Capturing CO2 emissions from SMR or gasification.
- Transporting and storing it underground.
- Transforms Grey Hydrogen to Blue Hydrogen.

Summary

- SMR is currently the dominant hydrogen production method.
- Alternative methods like gasification are available but pose emission challenges.
- Transitioning to cleaner production is the industry's biggest challenge.

Lecture 5.41

Electrolysis and Storage Issues

Agenda

- Principles of Electrolysis
- Types of Electrolyzers (PEM, Alkaline)
- Efficiency of Electrolysis
- Hydrogen Storage Methods Recap
- Storage Issues: Embrittlement
- Storage Issues: Boil-off & Leaks

Principles of Electrolysis

- Splitting water into hydrogen and oxygen using electricity.
- Anode reaction: Oxidation of water to produce O2.
- Cathode reaction: Reduction of water to produce H2.
- Requires direct current (DC).

Types of Electrolyzers

- Alkaline Electrolyzer (AEC): Mature technology, uses liquid electrolyte (KOH).
- Proton Exchange Membrane (PEM): Faster response, compact, uses solid polymer.
- Solid Oxide Electrolyzer Cell (SOEC): High temperature, high efficiency.

Alkaline vs PEM

Feature	**Alkaline**	**PEM**
Electrolyte	Liquid KOH	Solid Polymer
Dynamic Response	Slow	Fast
Cost	Lower	Higher
Maturity	Commercial	Commercial

Table: Electrolyzer Comparison

Efficiency of Electrolysis

- Typically around 60-80%.
- Energy losses as heat.
- High electricity cost makes Green H2 expensive currently.
- Decreasing costs of renewables is changing the economics.

Hydrogen Storage Issues

- Hydrogen is the smallest molecule.
- It can easily leak through materials that contain other gases.
- Requires specialized containment materials and seals.

Hydrogen Embrittlement

- Hydrogen atoms penetrate metals (especially steel).
- Causes a loss of ductility and tensile strength.
- Leads to catastrophic failure of pipes and tanks.
- Mitigation: Use of specific alloys or polymer linings.

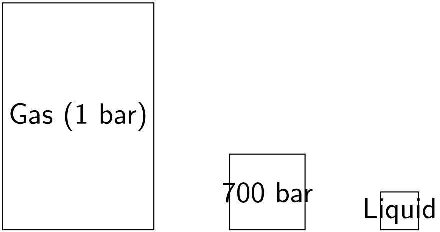
Boil-off in Liquid Storage

- Liquid hydrogen requires -253 C.
- Heat leaks into the tank cause vaporization (boil-off).
- Boil-off gas must be vented or re-liquefied to prevent tank rupture.
- Loss of product over time.

Solid State Storage

- Metal Hydrides: Hydrogen atoms bond with metals.
- Safer, operates at low pressure.
- Heavy and expensive.
- Slow charging and discharging rates.

Storage Volume Comparison



Visual representation of relative volumes for the same mass of H2

Summary

- Electrolysis is the key to producing clean, green hydrogen.
- PEM and Alkaline are the dominant technologies.
- Storage is plagued by issues like embrittlement and boil-off.
- Advanced materials are required for safe and efficient storage.

Lecture 5.42

Hydrogen Transportation

Agenda

- The Transportation Challenge
- Pipelines
- Tube Trailers (Compressed)
- Liquid Hydrogen Tankers
- Liquid Organic Hydrogen Carriers (LOHC)
- Ammonia as a Carrier

The Transportation Challenge

- Connecting production sites (often remote) to end-users.
- Low volumetric density makes transport expensive.
- Requires large infrastructure investments.
- Safety during transit is paramount.

Pipelines

- Most cost-effective for large volumes over long distances.
- Requires dedicated pipelines due to embrittlement issues.
- Blending with natural gas in existing grids (up to 15-20%) is possible.
- High initial capital expenditure.

Tube Trailers (Compressed)

- Transporting gaseous hydrogen at high pressures (200-500 bar).
- Suitable for short distances and small volumes.
- Flexible, point-to-point delivery.
- Low payload fraction (the steel tubes weigh much more than the hydrogen).

Liquid Hydrogen Tankers

- Transporting cryogenic liquid hydrogen via trucks or ships.
- Higher payload capacity than tube trailers.
- Costly liquefaction process.
- Boil-off during transport must be managed.

Transport Methods Comparison

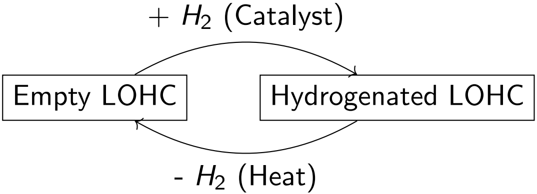
Method	Volume	Distance
Tube Trailer	Low	Short
Liquid Tanker	Medium	Medium/Long
Pipeline	High	Long
Ship (LOHC/NH3)	High	Intercontinental

Table: Transport Method Suitability

Liquid Organic Hydrogen Carriers (LOHC)

- Hydrogenate an organic liquid (like toluene) to store H2.
- Can be transported safely at ambient conditions like oil.
- Dehydrogenate at the destination to release H2.
- Requires heat for dehydrogenation.

LOHC Cycle



Ammonia (NH_3) as a Carrier

- Ammonia has high hydrogen density.
- Easier to liquefy (-33 C) than hydrogen.
- Existing global infrastructure for ammonia transport.
- Can be cracked back into H_2 or used directly.

Economics of Transport

- Transport costs can double the delivered price of hydrogen.
- Optimal method depends entirely on volume and distance.
- Local production (decentralized) avoids transport costs but loses economies of scale.

Summary

- Pipelines are best for large scale, long distance.
- Tube trailers for small, short range distribution.
- LOHCs and Ammonia are key for global, maritime hydrogen trade.
- Infrastructure development is a massive hurdle.

Lecture 5.43

Fuel Cells: Principles and Types

Agenda

- What is a Fuel Cell?
- Basic Principle of Operation
- Thermodynamics of Fuel Cells
- Types of Fuel Cells
- PEMFC vs SOFC
- Advantages and Limitations

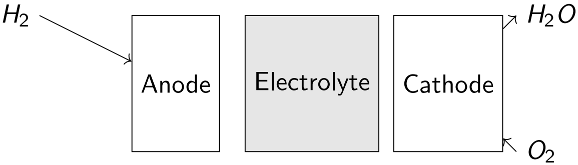
What is a Fuel Cell?

- An electrochemical device that converts chemical energy directly into electrical energy.
- Unlike batteries, they do not need recharging; they run as long as fuel is supplied.
- Emits only water and heat when using pure hydrogen.

Basic Principle of Operation

- Consists of an anode, a cathode, and an electrolyte.
- Hydrogen is fed to the anode, Oxygen (air) to the cathode.
- Catalyst splits H2 into protons (H+) and electrons (e-).
- Electrons flow through external circuit (electricity); protons flow through electrolyte.

Fuel Cell Schematic



Thermodynamics

- Not limited by Carnot efficiency.
- Maximum theoretical efficiency is related to Gibbs free energy.
- Practical efficiencies range from 40% to 60%.
- Cogeneration (using waste heat) can push overall efficiency ¿ 80%.

Types of Fuel Cells

- Classified primarily by the kind of electrolyte they employ.
- Determines the operating temperature and the type of fuel.
- Major Types: PEMFC, AFC, PAFC, MCFC, SOFC.

Polymer Electrolyte Membrane (PEMFC)

- Uses a solid polymer electrolyte.
- Low operating temperature (80 C).
- Fast startup times.
- Ideal for vehicles and portable applications.

Solid Oxide Fuel Cell (SOFC)

- Uses a hard, non-porous ceramic compound as the electrolyte.
- High operating temperature (800 - 1000 C).
- High efficiency, can reform fuels internally (methane).
- Used for large-scale stationary power generation.

Fuel Cell Comparison

Type	**Temp (C)**	**Efficiency**
PEMFC	80	40-50%
SOFC	800-1000	50-60%
MCFC	650	50%

Table: Comparison of common fuel cells

Advantages and Limitations

- Advantages: Zero emissions, high efficiency, quiet operation.
- Limitations: High cost (platinum catalysts), durability, lack of hydrogen infrastructure.

Summary

- Fuel cells convert chemical energy directly to electrical energy.
- PEMFCs are best for transport due to low temp and fast start.
- SOFCs are best for stationary power due to high efficiency and fuel flexibility.

Lecture 5.44

Fuel Cell Construction and Working

Agenda

- Components of a Fuel Cell
- Membrane Electrode Assembly (MEA)
- Bipolar Plates
- Gas Diffusion Layers (GDL)
- Working Mechanism (Step-by-step)
- Fuel Cell Stack

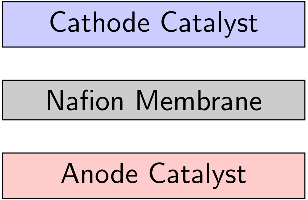
Components of a Fuel Cell

- A single fuel cell produces less than 1 Volt.
- To get useful voltage, many cells are combined into a 'Stack'.
- Main components: MEA, Bipolar plates, GDL, gaskets.

Membrane Electrode Assembly (MEA)

- The heart of the PEM fuel cell.
- Consists of a proton-conducting membrane sandwiched between two catalyst layers (anode and cathode).
- Catalyst is typically Platinum supported on Carbon nanoparticles.

MEA Cross-section



Bipolar Plates

- Conduct electrical current from cell to cell.
- Distribute reactant gases evenly over the active areas (flow fields).
- Remove product water from the cell.
- Made of graphite or coated metals.

Gas Diffusion Layer (GDL)

- Porous material (carbon paper or cloth).
- Allows gases to diffuse from bipolar plates to the catalyst layer.
- Manages water transport (hydrophobic treatment prevents flooding).
- Provides electrical contact.

Working Mechanism: Step 1

- Hydrogen gas flows through channels in the anode bipolar plate.
- Diffuses through the GDL to the anode catalyst layer.
- Platinum catalyst splits H2 into $2H^+$ and $2e^-$.

Working Mechanism: Step 2

- Protons (H^+) migrate through the polymer membrane to the cathode.
- Electrons (e^-) cannot pass through the membrane.
- Electrons travel through the external circuit, providing electrical power.

Working Mechanism: Step 3

- Oxygen (from air) flows to the cathode catalyst.
- Oxygen reacts with incoming protons and electrons.
- Reaction produces water and heat:
  $1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$.

The Fuel Cell Stack

- Individual cells are stacked in series.
- Voltage adds up: $V_{total} = V_{cell} \times N_{cells}$.
- Requires balance of plant (BOP): pumps, blowers, cooling loops.

Summary

- The MEA is the core where the electrochemical reactions occur.
- Bipolar plates and GDLs ensure proper gas distribution and current collection.
- Cells are stacked to achieve desired voltage and power output.

Lecture 5.45

Hydrogen Safety and Future Outlook

Agenda

- Properties Affecting Safety
- Flammability and Explosivity
- Leak Detection and Mitigation
- Standards and Regulations
- The Hydrogen Economy
- Future Prospects

Properties Affecting Safety

- Lightest gas: highly buoyant, disperses quickly in open areas.
- Colorless, odorless, and tasteless: difficult to detect leaks by human senses.
- Small molecule: prone to leaking through seals and embrittling metals.

Flammability and Explosivity

- Wide flammability range: 4% to 75% in air.
- Low ignition energy: can be ignited by a static spark.
- Burns with a pale blue, almost invisible flame.
- High risk of detonation in confined spaces.

Gas Properties Comparison

Property	Hydrogen	Methane
Flammability Limit	4-75%	5-15%
Min Ignition Energy	0.017 mJ	0.274 mJ
Flame Visibility	Poor	Good
Buoyancy in air	Very High	High

Table: Safety related properties

Leak Detection and Mitigation

- Requires specialized sensors (thermal conductivity, electrochemical).
- Facilities must be designed with high ventilation (roof vents).
- Odorants are hard to add because hydrogen is so light (odorants separate).
- Flame detectors must be sensitive to UV/IR since flames are invisible.

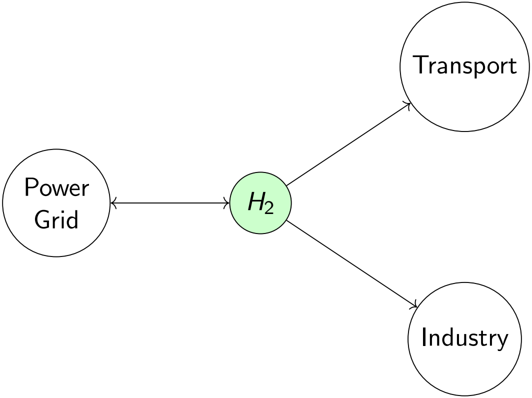
Standards and Regulations

- Strict codes govern storage pressure, material selection, and zoning.
- ISO 14687: Hydrogen fuel quality standards.
- NFPA 2: Hydrogen Technologies Code.
- Safety by design is paramount.

The Hydrogen Economy

- Vision of using hydrogen as a primary energy carrier replacing fossil fuels.
- Integrates renewable energy with transport, industry, and heating.
- Provides a solution for seasonal energy storage.

Sector Coupling



Challenges to the Future

- Cost reduction of green hydrogen production (electrolyzers).
- Massive infrastructure investment (pipelines, refueling stations).
- Policy support and carbon pricing.
- Public perception of safety.

Future Prospects

- Decarbonization of heavy industry (steel, cement).
- Aviation and maritime shipping fuels (e-fuels, ammonia).
- Global hydrogen trade markets (export from sunny/windy regions).
- Hydrogen Valleys and Hubs.

Course Summary

- Hydrogen requires rigorous safety protocols due to its unique properties.
- Despite challenges, it is indispensable for achieving net-zero emissions.
- This concludes Thermal Engineering-II. Thank you!