Combustion in CI Engines and Gas Turbines

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ME 417: Internal Combustion Engines

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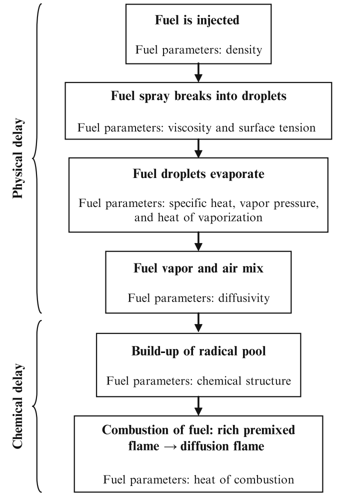
Essential Features of CI Combustion



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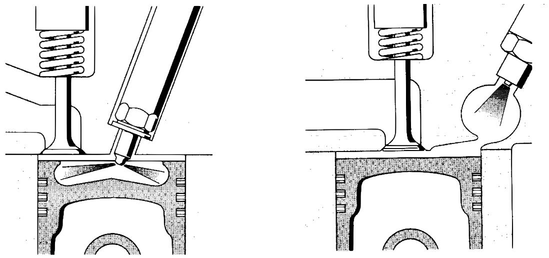
- Air alone is compressed in a CI engine and fuel is injected into the cylinder towards the end of the combustion stroke.
- Liquid fuel, injected at high velocity as one or more jets through small orifices or nozzles in the injector tip, atomizes into small drops and penetrates into the combustion chamber. Fuel vaporizes and mixes with the high-temperature high-pressure cylinder air.
- Since the air temperature and pressure are above the fuel's ignition point, spontaneous ignition of portions of already-mixed fuel and air occurs after a delay period of few crank angle degrees.
- Cylinder pressure increases as combustion of fuel-air mixture occurs. Consequent heating and compression of unburned portion of charge shortens the ignition delay and fuel vaporization time.
- Fuel injection continues until desired amount of fuel is injected. Atomization, vaporization, fuel-air (also burned gases) mixing, and combustion continues until combustion process is completed.

- Injection timing is used to control combustion timing and short ignition delay period is desirable.
- Engine torque is varied by varying the amount of fuel injected per cycle with essentially unchanged air flow. Engine is operated un-throttled with good part-load efficiency relative to SI engine.
- As fuel injection per cycle is increased, problem with air utilization leads to shoot formation which cannot be burned up prior to exhaust. Soot formation limits the maximum fuel/air ratio to values 20% or more lean of stoichiometric and consequently lower mean effective pressure than SI engine.
- Since diesel always operates with lean fuel/air ratios and higher values of $\gamma (= C_p/C_v)$ over expansion stroke gives higher conversion efficiency than SI engine.

Two Categories of Diesel Combustion Systems

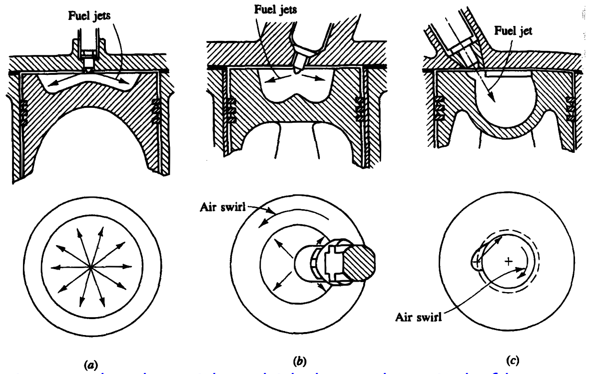
1. Direct-injection (DI) Engines
2. Indirect-injection (IDI) Engines



e742 Direct injection diesel engine In-Direct injection diesel engine

⊙ IDI engine designs are only used in the smallest engine sizes.

Direct Injection (DI) Systems



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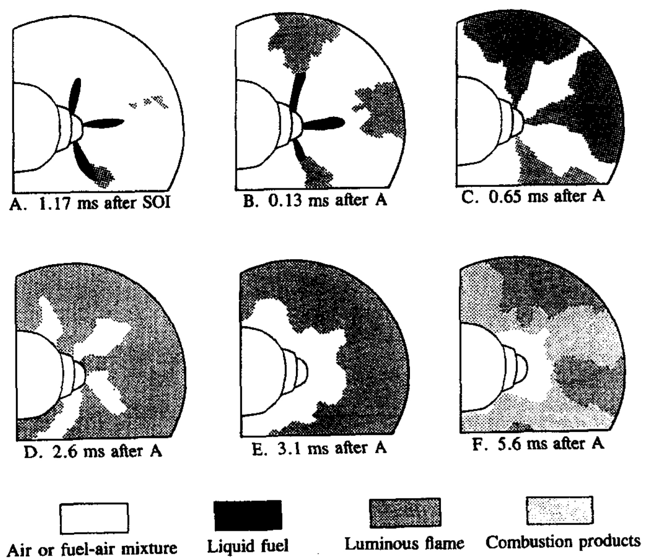
(a) quiescent chamber with multi-hole nozzle typical of larger engines;
(b) bowl-in-piston chamber with swirl and multi-hole nozzle;
(c) bowl-in-piston chamber with swirl and single-hole nozzle.
(b) and (c) used in medium to small DI engine range.



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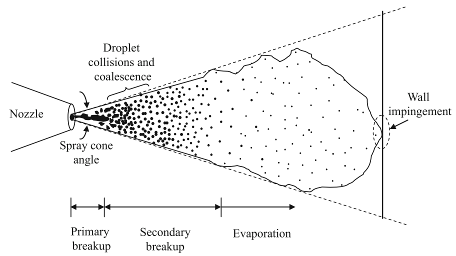
Phases of a DI Engine Combustion

- In compression stroke, air alone is compressed and raised to a high temperature. One or more jets of fuels, compressed to a pressure of 100-2000 bar is injected into the engine cylinder.
- **Physical Delay:** Fuel jet disintegrates into a core of fuel surrounded by a spray envelope created by atomization and vaporization of fuel. At some location in the spray envelope a mixture of air and fuel will form and oxidation becomes imminent.



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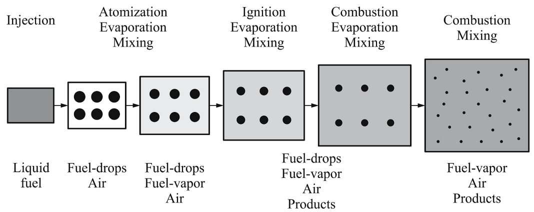
- **Chemical Delay:** Reaction starts slowly and then accelerates until inflammation or ignition takes place.
  Ignition Delay = Physical Delay + Chemical Delay.
- Rapid pressure rise occurs because of the myriad ignition points and the accumulation of fuel in the delay period. Following the stage, the final portion of the fuel are injected and consequently combustion is regulated by the injection rate. Since the process is far from homogeneous, combustion continues when the expansion stroke is well under way.



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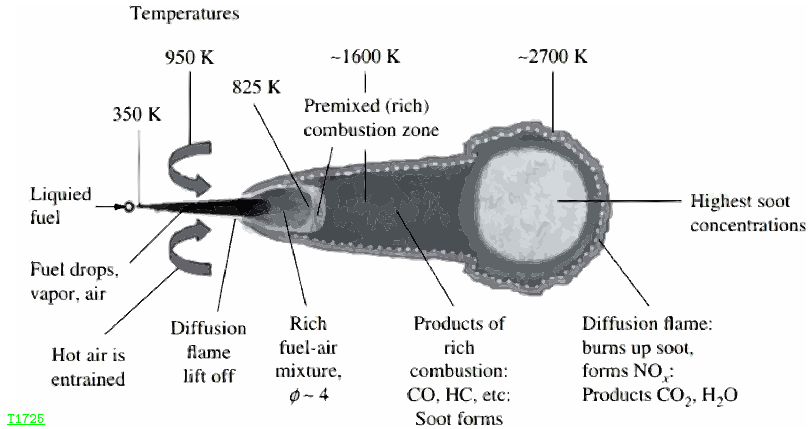

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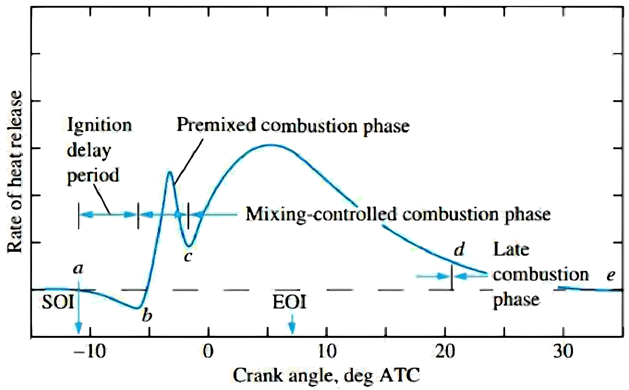
Key features, and gas temperature distribution, in a DI diesel fuel spray: injection, atomization, air entrainment, premixed-combustion process, soot formation region, diffusion -flame location, and lift-off distance from nozzle orifice.



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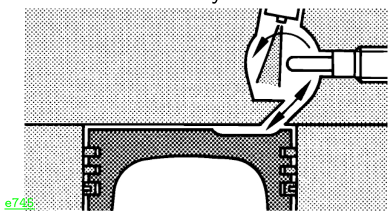
1. Ignition Delay (ab)
2. Premixed or Rapid Burning Phase (bc)
3. Mixing Controlled Combustion Phase (cd)
4. Late Combustion Phase (de)

Indirect-Injection (IDI) Systems

IDI systems have divided combustion chamber and rich mixtures in the auxiliary chamber with relatively lean charges in the main chamber are used to achieve extremely low NOx and HC emissions.



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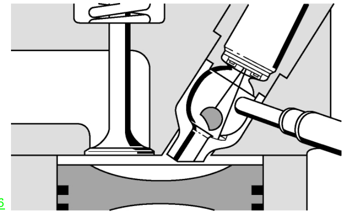
(a) Swirl chamber system



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(b) Pre-chamber system

Swirl chambers rely on the ordered motion to raise combustion speed, and pre-chambers rely on turbulence to increase combustion speed. Both types uses heat-resistant inserts which is quickly heated up by the combustion process, and then helps to reduce ignition delay.

Knock in CI Engines

The problem of knock in CI engine is complicated by the added complexity of the physical delay period which is influenced by:

1. the density and temperature of air in the cylinder
2. the atomization, penetration and shape of the spray
3. the properties of the fuel, such as volatility and viscosity, which affect the spray characteristics
4. the turbulence of air, which promotes mixing.

To **reduce** the possibility of knock in CI engines, fuel/air should have:

- A high temperature
- A high density
- A short delay
- A reactive mixture

Temperature Factors in Reducing CI Knock

Decreasing the temperature of the initially formed mixture by any of the following methods will **increase** the possibility of knock:

- Lowering the compression ratio
- Lowering the inlet air temperature
- Lowering the coolant temperature
- Lowering the cylinder and cylinder walls temperature
- Advancing or retarding the start of injection

⊙ Injection of fuel after TDC will reduce knock (and power) because of the pressure impact is relieved by the expansion stroke.

Density Factors in Reducing CI Knock

Decreasing the temperature of the initially formed mixture by any of the following methods will **increase** the possibility of knock:

- Decreasing the inlet air pressure
- Decreasing the compression ratio

Thus raising the compression ratio and supercharging the CI engine, unlike in the SI engine, tends to reduce knock.

Time Factors in Reducing CI Knock

Increasing the amount of fuel in the initially formed mixture, or increasing the time for forming a homogeneous mixture, by any of the following methods will **increase** the possibility of knock:

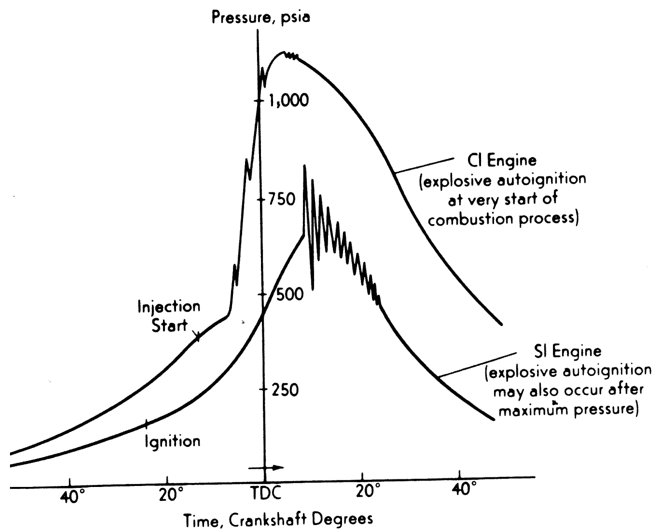
- Decreasing the turbulence of the compressed air
- Increasing the speed of the engine
- Decreasing the injection pressure
- Increasing the rate of injection

Composition Factors in Reducing CI Knock

The possibility of knock in CI engine is **decreased** by the following factors:

- Raising the Cetane rating of the fuel (decreasing chemical delay)
- Increasing the volatility of the fuel (decreasing physical delay)
- Decreasing the viscosity of the fuel (promoting mixing and therefore decreasing physical delay).

⊙ Fuels with high Cetane rating may be undesirable for particular engine since the rise of combustion may be too gradual. Thus, Cetane rating of 40-60 are usually specified. If the Cetane rating is too low, starting of the engine may be difficult. With high Cetane values, the ignition delay may be too short to allow the adequate mixing of fuel with air, and incomplete combustion may result.



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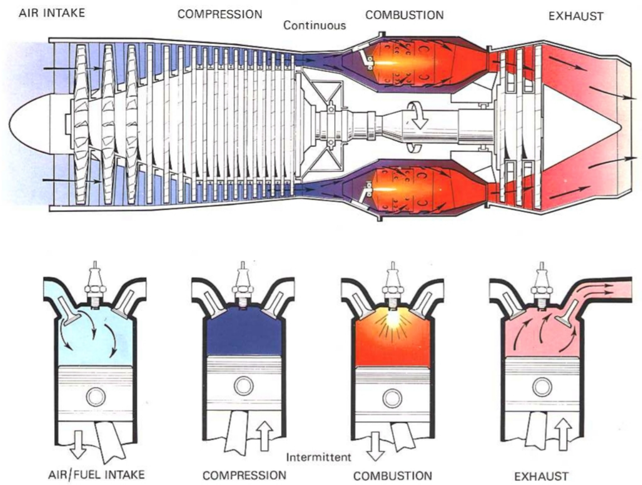
GT Operating Parameters

- GT combustors operates at pressures of 3 atm for small engines to as high as 40 atm for advanced engines. Aircraft engines operate at compression ratios of 20/1 to 40/1, while stationary units operate at 10 to 15 atm.
- Combustor outlet temperatures are set by the metallurgical requirements of the turbine blades and range from 1300 to 1700°C for aircraft turbines and 1000 to 1500°C for stationary turbines.
- Combustor inlet temperature depends on the compressor pressure ratio and ranges from 200 to 500°C. The highest cycle efficiency is achieved with the highest feasible turbine inlet temperature.
- Since the stoichiometric flame temperatures of GT fuels is 2000°C or more, 100 to 150% excess air is used to cool the combustor liner to a suitable operating temperature around 800°C.



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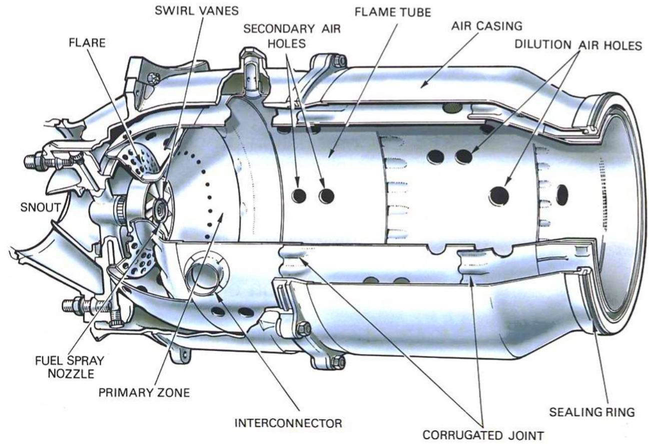
Combustion in GT

Fuel in GT is burned almost stoichiometrically with 25 to 35% of the air entering the combustor. The combustion products mix with the remaining air to arrive at a suitable temperature for the turbine. All combustors have the following three zones:

1. **Recirculation zone**: fuel is evaporated and partially burned.
2. **Burning zone**: fuel air mixture burning is completed.
3. **Dilution zone**: dilution air is mixed with hot gas.



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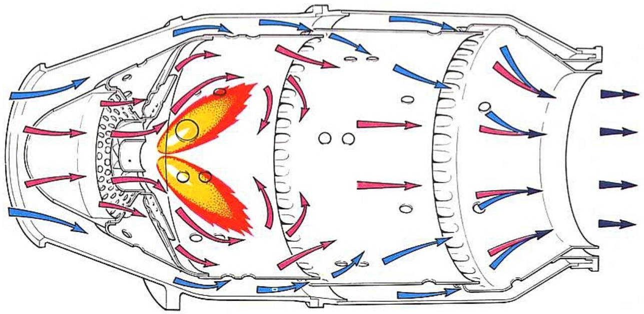

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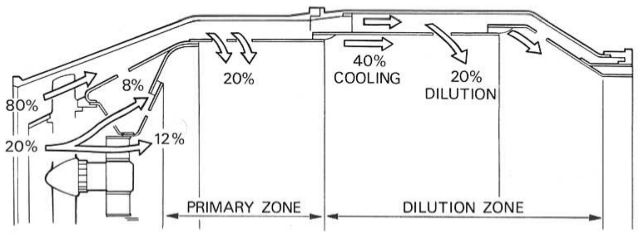

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