جامعة ديالى/ كلية الهندسة
قسم الهندسة الكيمياوية

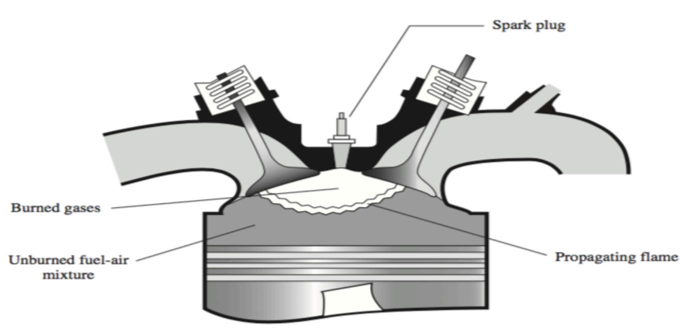
المرحلة الثالثة
هندسة الاحتراق
(1)

1. Definition:

Combustion is the most important reaction to the human race. The term 'combustion' refers to a rapid exothermic chemical reaction between a fuel and an oxidizer which transforms chemical energy (stored in chemical bonds) to heat and light. A fuel is a combustible material which releases energy in terms of heat and light when it is combusted. The oxidizer is a chemical substance which is required for the fuel to burn, the most common oxidizer is oxygen. The visible part of a fire in the gas phase, the reaction zone, is called flame. It is used in power generation, land, sea and air transportation, spacecraft propulsion, heating, material processing and other technologies. It occurs in industrial furnaces and boilers, smelters, kilns, ovens, incinerators, engines and domestic stoves, in mobile and stationary applications.

2.Modes of Combustion and flames

Combustion can occur in either a **flame** or **non-flame** mode, and flames, in turn, are categorized as being either **premixed** flames or **non-premixed (diffusion) flames**. The difference between flame and non-flame modes of combustion can be illustrated by the processes occurring in a knocking spark-ignition engine. we see a thin zone of intense chemical reaction propagating through the unburned fuel–air mixture. The thin reaction zone is what we commonly refer to as a flame. Under certain conditions, rapid oxidation reactions occur at many locations within the unburned gas, leading to very rapid combustion throughout the entire volume of the charge, that is, the reaction is not limited to a well-defined reacting region called flame. This essentially volumetric heat release in an engine is called **Autoignition**, and the very rapid pressure rise leads to the characteristic sound of engine knock. The two classes of flames, **premixed** and **non-premixed (or diffusion)**, are related to the state of mix of the reactants, as suggested by their names. In a premixed flame, the fuel and the oxidizer are mixed prior to the occurrence of any significant chemical reaction. The spark-ignition engine is an example where premixed flames occur. Contrarily, in a diffusion flame, the reactants are initially separated, and reaction occurs only at the interface between the fuel and oxidizer, where mixing and reaction both take place. An example of a diffusion flame is a simple candle.



3. Fuels

A fuel can be considered as a finite resource of chemical potential energy in which energy stored in the molecular structure of particular compounds is released via complex chemical reactions. Chemical fuels can be classified in a variety of ways, including by phase and availability **as** shown in Table **1.2** Some of the basic requirements of a fuel include: high energy density (content), high heat of combustion (release), good thermal stability (storage), low vapor pressure (volatility) and non-toxicity (environmental impact).

Table 1.2: Classification of chemical fuels by phase and availability [6]. Reproduced by permission of Marcel Dekker Inc.

Naturally available	Synthetically produced
Solid	
Coal	Coke
Wood	Charcoal
Vegetation	Inorganic solid waste
Organic solid waste	
Liquid	
Crude oil	Syncrudes
Biological oils	Petroleum distillates
Fuel plants	Alcohols
	Colloidal fuels
	Benzene
Gas	
Natural gas	Natural gas
Marsh gas	Hydrogen
Biogas	Methane
	Propane
	Coal gasification

3.1. Solid-fuel

Solid fuels are characterized by their heating values (calorific values). From solid fuels, heat and power can be produced directly. They can also be converted into liquid and gaseous fuels. Naturally available solid fuels include wood and other forms of biomass, lignite, bituminous coal, and anthracite. The modem trend is to go on for clean and efficient fuels with small sized furnaces where solid fuels cannot compete with liquid and gaseous fuels. But because they are cheap and easily available, solid fuels still supply approximately 35%of the total energy requirements of the world. The world's most prominent natural solid fuel resource is coal. Coal, remnants of plants and other vegetation that have undergone varying degrees of chemical conversion in the biosphere, is not a simple homogeneous material but rather is a complex substance having varying chemical consistency. Plant life first begins to decay by anaerobic, or bacterial, action, often in swamps or other aqueous environments, producing a material known as peat. The decomposing material is next covered and folded into the earth's crust via geological action that provides extreme hydrological pressure and heating required for the coal conversion process, as well as an environment that drives off volatile and water, this complex transformation, or coalification process, results in changes, or metamorphosis, over great periods of time and in a variety of fuels ranging from peat, which is principally cellulose, to hard and black coal.

3.2. Liquid-fuel

Liquid fuels are easy to transport and to handle. As liquids have a 10^3 higher density than gases, the energy density of liquid fuels is generally significantly higher than that of even highly compressed gases. Common liquid fuels are hydrocarbons and alcohols. They have widespread use as transportation fuels. Liquid fuels can be produced from crude oil (petroleum) by fractionated distillation and further processing, from other fossil sources such as coal and natural gas, or from biomass. Similarly, to coal, petroleum is a fossil fuel. It has formed from the fossilized remains of plants and animals over geologic time scales at high temperatures and high pressures under the ground. It is pumped to the surface and processed in refineries. Apart from fuels which are liquid at ambient conditions, liquefied gases under high pressure or cold temperatures are used (CNG, LPG, liquefied hydrogen, etc). Common liquid transportation fuels are gasoline, diesel, kerosene and fuel oil.

3.3. Gaseous-Fuel

Gaseous fuels are the most convenient fuel, which present the least difficulty from the standpoint of mixing with air and distributing homogeneously to the various cylinders in a multi-cylinder engine, or burners in a gas turbine, furnace or jet engine. Under good combustion conditions, they leave relatively little combustion deposits as compared with other fuels. However, gaseous fuels for automotive equipment necessitate the use of large containers and restrict the field of operation. Gaseous fuels may be divided into four types:

(a) Fuels gases found in nature

- Natural gas
- Coal mine gas

(b) Gases produced from solid fuel

- Producer gas
- Water gas
- Gases derived from coal (coal gas)
- Gases derived from waste and Biomass (e.g. wood gas)
- From other industrial processes (e.g. blast furnace gas)

(c) Gases produced from petroleum

- Liquefied Petroleum gas (LPG)
- Gases from oil gasification

(d) Gases obtained from some fermentation processes

Beside these, hydrogen and acetylene are two important gases those are widely used in the industries.

4. Historical Perspective of Combustion Technology

Here is a brief and incomplete overview concerning the early engineering applications of combustion.

4.1. Lighting

Before the discovery of electricity, flames from wood, oil lamps, gas lamps, and candles were used to provide lighting. Some of the earliest lamps used a wick to draw oil from a reservoir to sustain a flame. In 1780 the Swiss physicist and chemist **(Ami Argand)** invented the tubular wick which significantly improved the brightness of the lamp see Fig. 1.8. The basic idea was to have a cylindrical wick to allow air to flow through and around it, significantly increasing the light intensity. A cylindrical chimney stabilized the flame, and along with a mechanism for adjusting the height of the wick, the resulting Argand flame burned efficiently, brightly, and also cleanly. **Benjamin Thompson** improved Argand's concept into astral lamp design in 1810. Thompson's improvements include the introduction of a barometric fuel level supply and a rack-and-pinion wick adjustment. Thompson possibly also contributed by allowing air to flow through the center of the wick and around the wick exterior to increase the flame volume and brightness. He also added a glass chimney to help control the airflow around the flame. In 1890, Austrian scientist and inventor, **Von Welsbach**, invented the first modern gas mantle see Fig. 1.9.

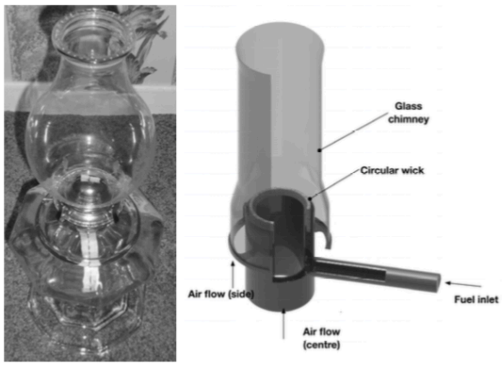


Fig. 1.8. A modern day Argand Lamp (photo taken by T. Ting, drawing created by N. Cao).

Fig. 1.9. A 21st century gas mantle (photo taken by T. Ting).

4.2 Steam Boilers

The earliest boilers operated by heating a kettle of water from the bottom and directing the steam through a narrow opening. By the 1700s, enclosed furnaces were used to direct more heat to the boiler kettle. Not until the 1750s were fire-tube boilers, where flue gas flowed inside tubes wound through the water vessel, invented. These boilers were not safe to operate, however. In 1788, **James Rumsey** patented the first water-tube boiler. Instead of flue gas, water flowed inside the tubes while the heat was supplied on the outside; see Fig. 1.10. This boiler boosted capacity and was safer to operate. Nonetheless, these boilers were not very successful, due to construction problems including steam leaking and deposits building up in the tubes. It was not until 1856 that a truly successful water-tube boiler was designed by **Stephen Wilcox**.

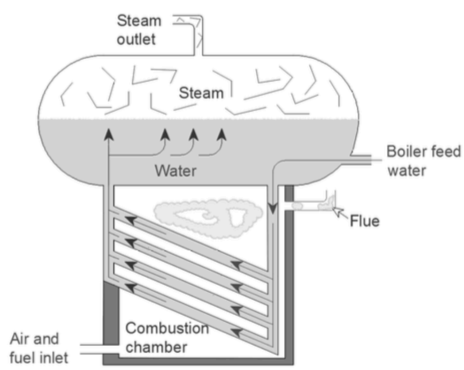


Fig. 1.10. A steam boiler (created by A. Ahmed).

4.3 Internal Combustion Engines

Internal combustion engines are devices that generate work using the products of combustion as the working fluid rather than as a heat transfer medium. To produce work, the combustion is carried out in a manner that produces high-pressure combustion products that can be expanded through a turbine or piston. In 1676, French clergyman, physicist, and inventor, **Jean de Hautefeuille** produced a concept of the internal combustion engine with gunpowder as the fuel. He was the first person to propose the use of a piston in a heat engine. In 1861, Belgian engineer **Étienne Lenoir** constructed the first production engine. On ignition, the piston flew to the top of the cylinder, uncovering exhaust ports which allowed the heated gases to escape. The piston then fell back due to gravity and cooling, and thus, did work (power stroke). In 1867, German engineer **Nikolaus August Otto** built the first spark ignition engine with compression. **Alphonse Eugène Beau de Rochas** is credited as the one who originated the principle of the four- stroke internal-combustion engine, and **Nikolaus Otto** is recognized as the inventor of the four-stroke internal-combustion engine. In the 1880 **Dugald Clerk** introduced the two-stroke engine concept. One major advantage of a two-stroke engine over its four-stroke counterpart is the much larger power-per-size (weight) of the engine. As such, two-stroke engines dominate in agile applications such as chainsaws and lawn mowers. In 1892, German inventor and mechanical engineer **Rudolf Christian Karl Diesel** invented compression-ignition engines, doubling the efficiency by permitting much greater compression ratios without the engine knocking (uncontrolled ignition and damaging combustion before desirable combustion occurs).

4.4 Gas Turbines

The gas turbine (figure below) operates in steady flow. Combustion air enters the turbine through a centrifugal compressor, where the pressure is raised to 5 to 30 atm, depending on load and the design of the engine. Part of the air is then introduced into the primary combustion zone, into which fuel is sprayed and bums in an intense flame. The gas volume increases with combustion, so as the gases pass at high velocity through the turbine, they generate more work than is required to drive the compressor. This additional work can be delivered by the turbine to a shaft, to drive an electric power generator or other machinery, or can be released at high velocity to provide thrust in aircraft applications. In 1791, English inventor **John Barber** patented a gas turbine which utilized a compressor, a combustor, and an impulse turbine. Like most patents, it was not practically realized, but first inventions such as this had a profound influence on subsequent development. In this case, it took a few years before the first working gas turbine emerged. In the 1880s, Norwegian inventor **Jens William Aegidius Elling** invented the first working gas turbine with a constant-pressure combustor. Elling is considered to be the father of the gas turbine. His first gas turbine patent was granted in 1884. Elling made the first turbine a reality in 1903. His original machine used both rotary compressors and turbines to produce (8 kW) net.

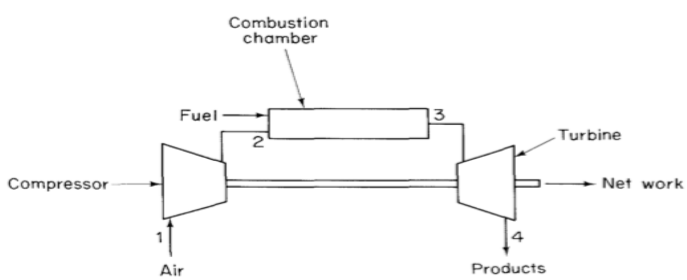


Figure 4.32 Gas turbine engine configuration.

4.5 Rocket engine

A rocket engine is a reaction engine that take their reaction mass from within the vehicle and form it into a high speed jet, obtaining thrust in accordance with Newton's third law. Most rocket engines are internal combustion engines, although non combusting forms exist. Classic rocket engines produce a high temperature, hypersonic gaseous exhaust. This is achieved by the combustion of oxidizer and a fuel, within a combustion chamber at high pressure. The hot gas produced is then allowed to escape through a narrow hole. One of the first devices to successfully employ the principles essential to rocket flight was the aeolipile. In AD 62, **Hero of Alexandria**, a Greek mathematician and engineer, described and invented an aeolipile, a steam-powered device. The aeolipile consisted of a spherical drum containing water along with two stream outlets pointing in the same circular direction. A fire was used to boil the steam, and the hot steam ejecting out through the two outlets caused the aeolipile to spin. The availability of black powder to propel projectiles was a precursor to the development of the first solid rocket. In ninth Century Chinese Taoist alchemists discovered black powder in a search for the elixir of life; this accidental discovery led to fire arrows which were the first rocket engines to leave the ground. Slow development of this technology continued up to the later 19th century, when Russian **Konstantin Tsiolkovsky** first wrote about liquid-fueled rocket engines. He was the first to develop the Tsiolkovsky rocket equation, though it was not published widely for some years.

The modern solid- and liquid-fueled engines became realities early in the 20th century, thanks to the American physicist Robert Goddard. Goddard was the first to use a De Laval nozzle on a solid-propellant (gunpowder) rocket engine. This was the birth of the modern rocket engine. He began to use liquid propellants in 1921 and was the first to launch, in 1926, a liquid-propellant rocket.