Engineering Combustion Essentials

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By

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Combustion is essential to human survival, and so is learning. This book aims at sparking inquisitive minds on fire, setting off a series of positive chain reactions which beautify everyday and future combustion.

"At times our own light goes out and is rekindled by a spark from another person. Each of us has cause to think with deep gratitude of those who have lighted the flame within us."
—Albert Schweitzer

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PREFACE

This book is primarily intended for introducing combustion to senior undergraduate and junior graduate students in mechanical and chemical engineering. Some undergraduate knowledge of thermodynamics and fluid mechanics is required to comprehensively appreciate the material.

ACKNOWLEDGEMENTS

This book could not be realized without grace from above, and the able hands of many gracious individuals. The author is particularly indebted to the following instrumental individuals for going way out of their way in helping him realizing this dream of his.

Prof. Dr. M. David Checkel, who gave the author the only combustion course, as a reading course. In the absence of formal lectures and lecture notes, the independent lifelong learning has been exceedingly painful and yet rewarding.

The Combustion Engineering classes from 2011 onward at the University of Windsor, for pointing out many obvious and not so obvious errors in the original manuscript, An Introduction to Combustion Engineering, 2011, Naomi Ting's Books, and also the revised version, Some Basics of Combustion Engineering, 2012, Naomi Ting's Books. Even after these two versions, Jamie Smith threw in his towel after proofreading the first couple of chapters. Lucas Semple made it much farther, ultimately more painfully to this author, Lucas gave many invaluable general comments which caused some serious sweating from the author. It took a proven marathon runner, Dr. Jacqueline Stagner, to endure the pain and correct all the bad jokes/English along with many subtle omissions such as commas and hyphens, from the beginning until the end. The leftovers, very tedious checking of symbols and nomenclature were effected by Junguo Wang and Yang Yang. They also straightened the references. When the manuscript failed to completely clear the 3 spot checks, Dr. Mehdi Ebrahimi and Yang Yang combed through the final version with different powerful software. Furthermore, Navjut Sandhu and Junguo Wang also double-checked some chapters. Even then, some errors escaped, but only to be caught by the powerful eyes of the marathon runner!

The author would still be drawing figures, if not for the following skillful and helping hands: Ashhar Ahmed, Saarah Akhand, Ning Cao, Fawas Hameed, Frank Iakovidis, Kristie Pearce, Navjot Sandhu, Naomi Ting, Tachelle Ting, Yoniana Ting, Zarek Ting, Junguo Wang, Hao Wu, Yang Yang, and Zhenyi Yang. Their names are ascribed underneath their artworks. Dr. Julia Aman produced the thermodynamic tables in the Appendix.

Mom, dad, sisters and brother; making fire and cooking aromatic wild plants still mesmerizes the author. There is no better place to experientially savor combustion other than the lush rainforest of Borneo island.

Naomi, Yoniana, Tachelle, and Zarek Ting, whose many sarcasms and love fueled the striving of this book over the years.

CHAPTER ONE

INTRODUCTION

"Success isn't a result of spontaneous combustion. You must set yourself on fire."
—Arnold H. Glasow.

Chapter Objectives

- Define combustion.
- Classify combustion into appropriate categories.
- Provide examples of combustion in engineering applications.
- Appreciate the general history of combustion science.
- Highlight Phlogiston Theory and Antoine Lavoisier.
- Convey the history of some combustion technologies.
- Present book outline.

Nomenclature

CI	compression ignition
HCCI	homogeneous charge compression ignition
SI	spark ignition

1.1 What is Combustion?

"Combustion is without exaggeration the most important reaction to the human race. All human and animal existence depends upon combustion as its course of energy." – G.G. Brown [1928]. In this book, the term 'combustion' refers to a rapid chemical reaction between a fuel and an oxidizer which produces heat and light. A fuel is a combustible material which releases energy in terms of heat and light when it is combusted. Wood is possibly the most classical and best known fuel. Within context, an oxidizer is a (chemical) substance which is required for the fuel to burn. As the word implies, the most common oxidizer is oxygen. In other words, combustion is a rapid exothermic chemical reaction which transforms chemical energy (energy stored in chemical bonds) to heat. An everyday example is a birthday candle, Fig. 1.1, where chemical energy stored in the wax is converted into both heat and light. Another example is a natural gas fire (place) as depicted in Fig. 1.2, which is used for keeping the indoor environment warm in the winter time.

Fig. 1.1. A birthday candle (photo taken by Y. Ting).

Fig. 1.2. A natural gas fire place (photo taken by Y. Ting).

Combustion can be divided into two main categories, flame versus non-flame (Table 1.1). Homogenous charge compression ignition (HCCI) is a well-known example of a flame-less (non-flame) combustion. HCCI is flame-less as the relatively slow (compared to typical combustion) reaction takes place throughout the entire volume of the charge, that is, the reaction is not limited to a well-defined reacting region called flame. Both flame and flame-less combustion can be further categorized into premixed and non-premixed types. When the fuel and the oxidant are well mixed (premixed) prior to reaching the reacting flame front, the flame is said to be premixed. The rate of combustion is not dependent on the fuel-oxidant mixing process for premixed flames. A Bunsen burner flame is a premixed flame that is stationary, whereas the premixed flame in a spark ignition (SI) engine is propagating.

A non-premixed flame occurs when the fuel and oxidizer are not premixed prior to combustion. The term ‘diffusion’ is also used interchangeably with ‘non-premixed,’ even though strictly it applies to the molecular diffusion of chemical species. The birthday candle in Fig. 1.1 is a diffusion flame. With heating, the wax melts, moves up along the wick and evaporates. The evaporated ‘wax’ diffuses from the wick outward while the oxidant diffuses inward. Combustion takes place in the region where the fuel-oxidant mixture composition is near stoichiometric. The energy conversion process in the prevailing compression ignition (CI) diesel engines is another applied example of non-premixed flame. It is worth mentioning that part of the combustion event in CI engines is premixed combustion. Nevertheless, the entire combustion process is governed by diffusion of the injected fuel and the compressed air in the engine cylinder.

Table 1.1. Classification of Combustion

Combustion		
Flame		Non-flame (Flame-less)
Premixed	Non-premixed	HCCI
Bunsen burner (stationary) SI engine (propagating)	Torch (gas) Lamp (liquid to gas) Candle (solid, liquid, gas) Match (solid)	

1.2 Combustion in Applications

Combustion is not only involved in, but is the essence of, many engineering applications. There are many everyday examples in power generation, built environment heating, cooking, and industrial processes.

In power generation, coal, oil, and natural gases are burned in furnaces to generate power and steam. More recently, biofuels such as wood chips and other biomass are also gaining acceptance. Even more common are the reciprocating engines, especially the aforementioned SI and CI engines, which combust liquid and gaseous fuels when converting chemical energy to useful work.

A natural gas furnace is still the dominant heating system for providing human thermal comfort in North American winters. Efficiencies in excess of 90% are quite typical for today's high-efficiency (two-stage) furnaces.

Figure 1.3 is a photo of a portable butane stove which is frequently used for making a 'steamboat' (Chinese fondue or hot pot). We note that commercial cooking, in particular, is dominated by the natural gas stove, such as that portrayed in Fig. 1.4. On the other hand, outdoor barbequing in North American summers is predominately done via propane barbeques. There is definitely a lot of room for improving these basic living necessities for better performance, saving both fuels and the environment. Thermodynamically speaking, converting electricity, presumably the highest quality energy, into heat, the lowest form (dustbin) of energy, for cooking purposes is a bad practice. Electric cooking is perhaps a lot more harmful to the environment than well-engineered combustion cooking.

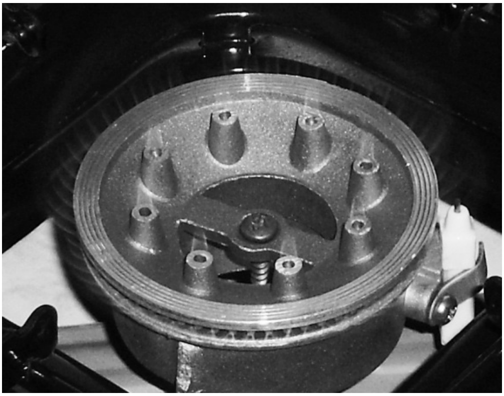

Fig. 1.3. A portable butane stove (photo taken by Z. Ting).

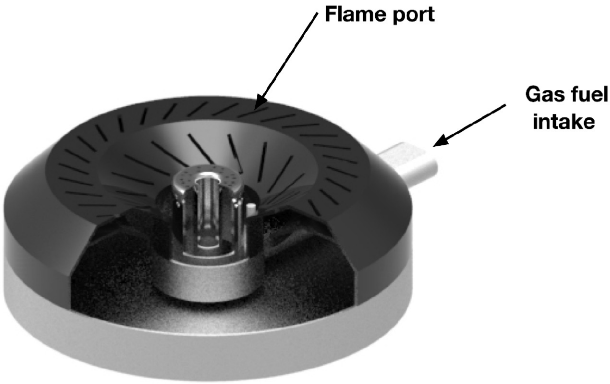

Fig. 1.4. A natural gas stove top (created by N. Cao).

Combustion is also at the core of many industrial processes such as metal processing, glass melting, and cement manufacturing, among many others. This class of combustion engineering applications is possibly least likely to be replaced by more renewable alternatives. Thus, efforts to ensure continuously cleaner and more efficient combustion in these areas are critical.

1.3 A Highlight of Combustion Science Development

In ancient Greek science, water, earth, air, and fire are the four fundamental elements of the world. Later, in part due to Plato and Aristotle, a fifth element aether (ether or quintessence) was added to the list. Eastern traditions, including Chinese and Indian, also have similar five basic elements. In context with combustion, fire crossed all these different cultures as one of the fundamental elements. Concerning fire, Greek mythology renders Prometheus in resolving the heat-deprived, shivering mankind with fire stolen from Mount Olympus. Factually, the following subsections give a brief walkthrough of historical combustion science development. The readers are forewarned that, while some first-discovery credits are sure, others are not so certain. In fact, there are records recognizing different persons as the first inventors. To some extent, this is expected, especially when they are contemporaries who have written about the ideas via less-than-formal vehicles, in different languages. In engineering, the further complication concerns granting more credit to the one who had the idea first, or the one who actually made the first working device or hardware, not to mention the exclusion of some lost history, especially those cultures where knowledge was primarily passed down through the generations orally. As more lost history is being uncovered, further clarification will emerge with time.

According to the Smithsonian [Smithsonian-Fireworks, 2017], somewhere between 600 and 900 AD, Chinese alchemists accidentally discovered the first version of gunpowder when mixing potassium nitrate with sulfur and charcoal. This eventually led to the use of gunpowder, black powder, or “fire drug” in weaponry. The earliest recording of gunpowder weaponry, including references to a gunpowder catapult, took place in 1046. On the celebration side, fireworks (Fig. 1.5) are an essential ingredient for occasions such as national days and new years. In these days, with abounding fingers pointing at combustion as a root cause behind many problems, it is next-to-impossible to make the public realize the utter dullness that would ensue if there were no fireworks.

Fig. 1.5. A cheerful combustion phenomenon – fireworks in display (photo taken by K. Pearce).

1.3.1 The Phlogiston Theory

The German alchemist and physician Johann Joachim Becher [1635-1682] replaced two of the four ancient Greek fundamental elements, fire and air, with three forms of earth, *terra lapidea*, *terra fluida*, and *terra pinguis* [Conant, 1950]. According to Becher's Physical Education published in 1667, he believed that *terra pinguis* was released when combustible substances were burned. Later, Georg Ernst Stahl, professor of medicine and chemistry, renamed *terra pinguis* as phlogiston. The phlogiston theory states that a substance loses its phlogiston into the air via burning; see Fig. 1.6. In other words, part of the substance before burning is phlogiston, and thus, the substance weighs less after losing its phlogiston to air. A down-to-earth example is cremation, where a typical adult will be left with approximately 3% of the original body weight in terms of ashes. Thus, our bodies are highly phlogisticated. As phlogiston is "essence" or "soul," we may say that human beings are largely 'spiritual beings.'

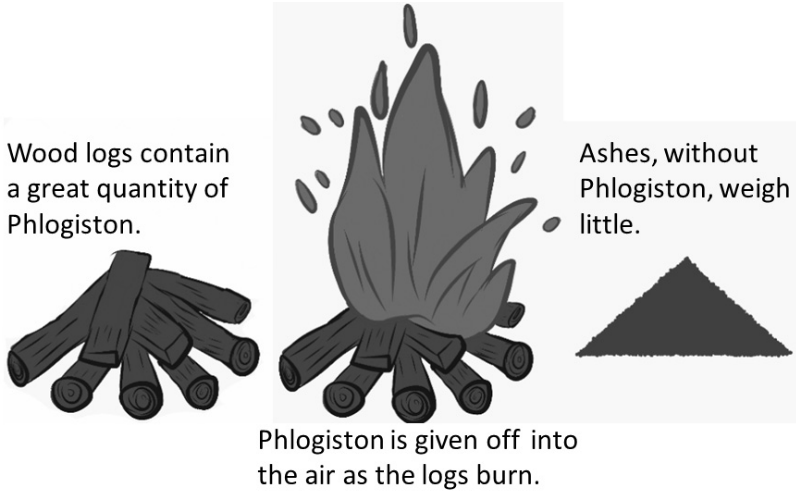

Fig. 1.6. Phlogiston is lost into the air when a substance burns (created by S. Akhand).

1.3.2 Antoine Lavoisier

Antoine Lavoisier [1743-1794] was a French Chemist who is regarded as "the Father of Modern Chemistry" or "the Father of Combustion" [ACS, 1999, Lavoisier, 1967]. He came from a rich family whose father wanted him to be a lawyer, while his own passion was for science. As a good son, Lavoisier obtained a degree in law, but he never practised it. Instead, he spent literally all his time and energy on science. His passion and extreme-hard-work led him to be elected to the prestigious Academy of Science at the very young age of twenty-five. To facilitate his experimental research, he needed money and this presumably was the reason he became a tax collector.

Who could be a better assistant that one's better half? A notable contribution of Mrs. Lavoisier was the translation of many technical reports into English and Latin.

Employing careful measurements, Lavoisier found that something weighed more after burning, and this did not make sense at that time as this disagreed with the prevailing Phlogiston Theory. He thought that something in the air had caused the weight increase. Lavoisier used a glass enclosure to cover phosphorus over a pool of mercury. When focussing sun rays through a lens onto phosphorus enclosed in a glass jar over a pool of mercury, Lavoisier found that the formation of phosphorus calx was associated with a corresponding rise in the mercury level. Additional experiments along this line (phosphorus, sulphur, tin) consistently led to a decrease of about one fifth of the air, thus Lavoisier realized that there was something in the air that played a vital role in the burning. It was his encounter with Clergyman Joseph Priestley that confirmed the discovery of oxygen. Lavoisier's extended series of rigorous efforts, particularly via careful measurements, eventually solidified in his Réflexions sur le Phlogistique, putting the false phlogiston belief to rest.

Lavoisier's involvement with politics, as a tax collector for the king to fund his lab, ended up causing him his life. He was sentenced to die on a guillotine at the age of 51, after the French Revolution.

1.3.3 Other Combustion Milestones

Other notable combustion milestones include that made by Robert Bunsen [1811-1899], who extensively studied a wide range of gaseous premixed flames. Specifically, Bunsen measured flame temperature and flame speed using a Bunsen burner (Fig. 1.7) starting in 1855 [Jensen, 2005]. He also collected flame enthalpy data with the help of a calorimeter.

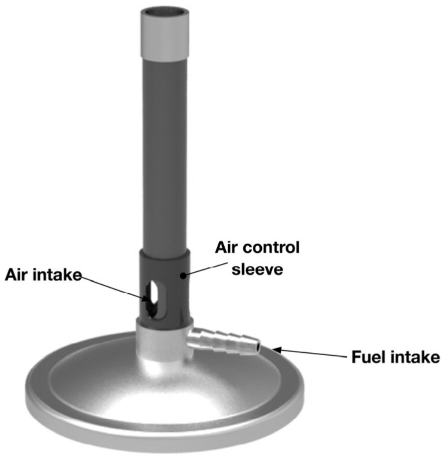

Fig. 1.7. A Bunsen burner (created by N. Cao).

Mallard and Le Châtelier [1883] were probably the first to propose a theory on flame propagation, and also the first researchers who documented the effects of turbulence on flame propagation. According to Mallard and Le Châtelier, Schloesing and de Mondesir were the first to note turbulence enhancement in combustion in 1864 [Woodbury et al., 1921].

Research on detonation was initiated by Chapman and Jouguet around 1900 [Chapman, 1899, Jouguet, 1905]. They differentiated the supersonic combustion phenomenon from the then somewhat better known subsonic deflagration.

The first combustion text was written in German by W. Jost [1903-1988] in 1938, which was later translated into English by H.O. Croft in 1946 [Jost, 1946]. World War II led to the momentous development of gas turbines and rockets. Subsequently, Lewis and von Elbe wrote the second combustion text (the first combustion text in English), in 1951 [Lewis & von Elbe, 1951]. It is worth mentioning that there were precursors, that is, earlier published documents which contained partial contents of the final monographs. For example, Lewis and von Elbe used the same title in their earlier 'book' published in 1938 by Cambridge University Press. As such, which book or author should be credited with the inauguration of the first combustion book is somewhat arguable.

1.4 Historical Perspective of Combustion Technology

Here is a brief and incomplete overview concerning the early engineering applications of combustion. Only four areas of combustion technologies are succinctly presented to illustrate their historical progression and significance.

1.4.1 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 utilized a wick to draw oil from a reservoir to sustain a flame.

It is generally recognized that it was in 1780 that the Swiss physicist and chemist François Pierre Ami Argand [1750-1803] invented the tubular wick which significantly improved the brightness of the lamp [Saltzman, 1999]; 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 (five to ten times brighter than a candle). 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.

In 1784, Jean-Pierre Minckelers [1748-1824] used pyrolyzed coal for gas flames [Cleveland & Morris, 2014]. He enclosed oil in the barrel of a gun and heated it in a forge to produce the much lighter gaseous fuel.

According to Borman and Ragland [1998], it was Benjamin Thompson who 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 centre 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.

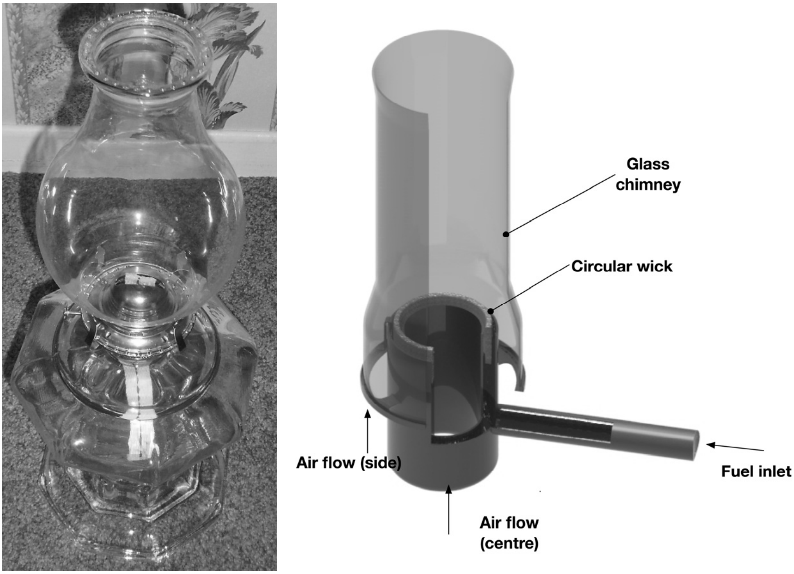

Fig. 1.8. A modern day Argand Lamp (photo taken by T. Ting, drawing created by N. Cao).

In 1890, Austrian scientist and inventor, Carl Auer Freiherr von Welsbach [1858-1929], invented the first modern gas mantle [Welsbach, 2018]; see

Fig. 1.9. Von Welsbach's invention was considered 'modern' because it was not the first or original invention. In other words, there were some previous designs including the Clamond basket invented in the 1880s by the Parisian, Charles Clamond [Clamond, 2018]. In 1885, Welsbach received a patent for his gas mantle design, consisting of 60% magnesium oxide, 20% lanthanum oxide, and 20% yttrium oxide. These original mantles gave off a green-tinted light. It was not until 1890 that Welsbach used cotton fabric soaked with a salt solution containing thoria and ceria, i.e., 99% thorium dioxide and 1% cerium (IV) oxide, to produce the first working mantles. The idea was to stabilize the flame on the mantle. It is worth noting that Welsbach is also known for his work on rare earth elements, which led to the development of the flint.

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

1.4.2 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 [1743-1792] patented the first water-tube boiler [Borman & Ragland, 1998]. 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 [1830-1893]. Within a few years, he and his life-long friend, George Babcock, founded Babcock and Wilcox Company in 1867 [ASME-Wilcox, 2017].

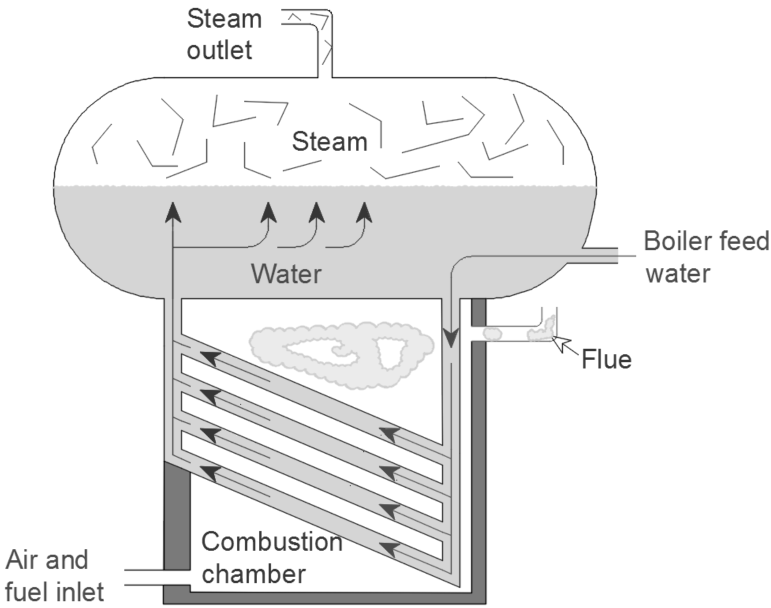

Fig. 1.10. A steam boiler (created by A. Ahmed).

1.4.3 Internal Combustion Engines

In 1673, Dutch mathematician, astronomer, physicist, horologist (one who possesses the art and science of measuring time), and author of early science fiction, Christiaan Huygens [1629-1695] (in a letter to his brother) gave the first indications that anyone had approached a working engine. In 1678, he designed a basic form of internal combustion engine fuelled by gunpowder [Huygens, 1680]. While there are those who said that he never successfully built one, other records state that he not only built it, but also demonstrated its power by lifting seven to eight boys into the air using a large demonstration unit [EOHT, 2017].

The aforesaid history is described somewhat different in Hautefeuille [2018]. In 1676, French clergyman, physicist, and inventor, Jean de Hautefeuille [1647-1724] 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. It is said that Huygens proposed a similar device two years later, in 1680, based on de Hautefeuille's suggestion, and it is possible that Huygens constructed some form of prototype; see Fig. 1.11. It is noted that de Hautefeuille tended to prematurely publish his ideas and rarely perfected his inventions, before abandoning them in favour of new pursuits. The Paris Academy of Sciences attested to the value and usefulness of many of his discoveries, but it never conferred on him the honour of electing him as a member.

In 1861, Belgian engineer Jean Joseph Étienne Lenoir [1822-1900] 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 the Lenoir cycle, an ideal gas undergoes a constant volume (isochoric) heat addition, an isentropic expansion, and a constant pressure (isobaric) heat rejection. Today’s reader may be surprised to learn that the first Lenoir engines operated only at approximately 3% efficiency. One must, however, keep in mind that these were the very first inventions; it took years of undue striving to raise efficiencies to 30%.

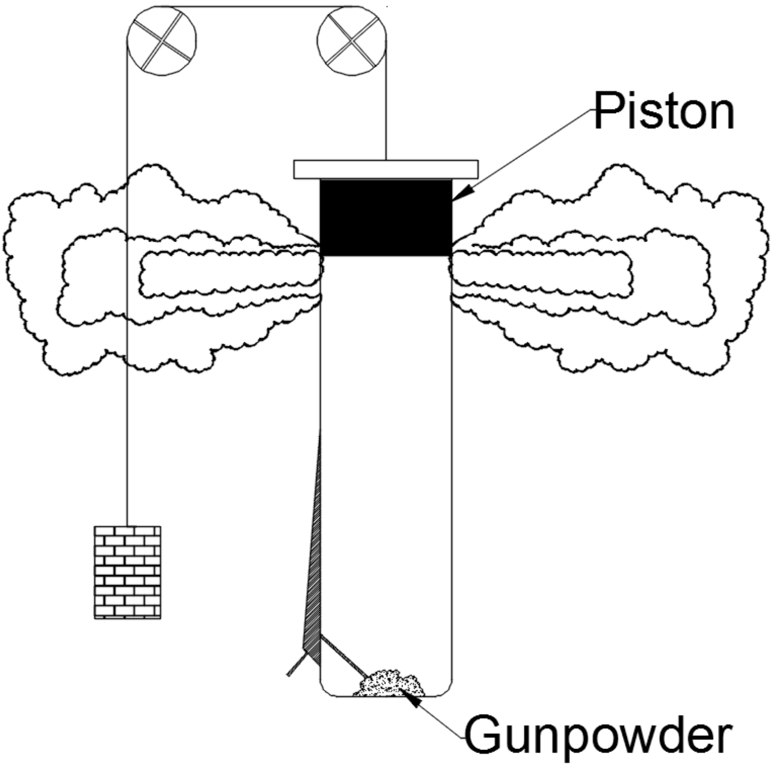

Fig. 1.11. Huygens' internal combustion engine (created by A. Ahmed).

In 1867, German engineer Nikolaus August Otto [1832-1891] built the first spark ignition engine with compression [McNeil, 1982]. Otto was originally inspired by Lenoir, and his first attempts in inventing a newer engine were with his brother. It is not clear, to be politically neutral, if Otto knew of French engineer de Rochas' 1862 patent on the four-stroke concept. While not everyone agrees, Alphonse Eugène Beau de Rochas [1815-1893] 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 1880s, two-stroke engines were developed. Dugald Clerk [1854-1931] introduced the two-stroke engine concept in 1880 [Clerk, 2018]. 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 [1858-1913] 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).

1.4.4 Gas Turbines

As early as AD 62, Hero of Alexandria [10-70 AD], a Greek mathematician and engineer, described and invented an aeolipile, a steam-powered device [Hero, 2018]. 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; see Fig.1.12. Apparently, this was undertaken and realized completely out of curiosity and fun. On the more practical side, it is interesting to note that among Hero's most well-known inventions was a wind wheel for harnessing wind on land.

In 1791, English coal master and inventor John Barber [1734-1801] patented a gas turbine which utilized a compressor, a combustor, and an impulse turbine [Barber, 2018]. 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 [1861-1949] invented the first working gas turbine with a constant-pressure combustor [Elling, 2018]. 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 11 bhp (8 kW) net.