The Internal Combustion Engine: Evolution and Impact

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Abstract

The internal combustion (IC) engine, the powerhouse of most vehicles for more than a century, was developed in the 1800s with continuous engineering improvements made even today. As per the name, the IC engine was built using the principles of combustion to turn fuel (such as gasoline or diesel) into energy that ultimately drives the wheels of the vehicle. It was designed so that the burning would occur inside the engine. Though rooted in one of the most common and widely-studied chemical reactions, successfully adapting this process for use in a vehicle engine presented many challenges for early pioneers in terms of consistency and reliability. Through scientific study combined with several prototypes, a functioning and commercially available IC engine laid the foundation of and transformed transportation and the automotive industry.

Over the years, IC engines have increased in design complexity of components and subsystems to meet changing requirements and improved efficiency based on different needs. In recent times, the growing concern over carbon emissions produced a new challenge, which has led to the research and development of alternative fuels and hybrid engines, all the while building on the mechanisms and features of previous models to accommodate and revolutionize powertrain technology. The report examines the evolution of the IC engine, highlighting its historical origin and consequential societal impact as well as its dynamic design transformation in response to the evolving needs of the world today.

Introduction

At the turn of the 19th century, the growing quest to improve mobility pushed many scientists and engineers to develop the internal combustion (IC) engine, a heat-powered motor ubiquitous in transportation technology even in the present day. The IC engine is widely used in land vehicles including cars, trains, trucks, and farm equipment such as tractors. It is also used in boats, ships, and airplanes, serving a multitude of different purposes. The invention of the IC engine was pivotal to the rise of the Technological Revolution, offering a paradigm and practical shift in the performance and efficiency of labour. During this period, the advancement in transportation, telecommunications, and electricity brought about significant socioeconomic change, using less time and energy to meet higher demands [1].

For instance, early innovators such as Étienne Lenoir and Nicolaus Otto introduced and paved the way for the design and functionalities of most car engines today using combustion to ignite fuel to perform useful work. Specifically, combustion (also known as burning) is a chemical reaction that occurs when a hydrocarbon fuel reacts with oxygen, producing carbon dioxide and water. Most importantly and for the purposes of the IC engine, this reaction is exothermic, meaning it produces energy which is harnessed inside a compartment of the engine known as the cylinder. This energy inside the engine is then delivered to the rest of the powertrain in a series of other steps [2].

As a result, understanding the processes and interconnections of the IC engine allows for the navigation of technological transitions in terms of performance and adapting to future changes. Due to the growth of technology towards the digital age, the mass global usage of the IC engine has pushed further innovation, allowing it to become more reliant and robust at the cost of harming the environment. The production of carbon dioxide gas from combustion is responsible for warming the atmosphere through the greenhouse effect, exacerbating climate change. By investigating the invention, design, and improvements of the IC engine, a holistic insight will be shed on its impact on human exchange and manufacturing.

Invention and Evolution

Although the IC engine was invented in the mid 1800s, its origin can be traced back thousands of years ago. For example, around 150 BC, the piston was used as an air pump for metalworking, harnessing the concept of compression and expansion of air that is essential to the IC engine. As it follows, the piston-cylinder system was later used in steam engines. However, steam engines (considered external heat engines) were bulky, impractical, and provided insufficient thermal energy. Thus, the idea of a compact unit capable of producing high thermal energy contained within itself arose [3].

Consequently, the concept of internal combustion evolved to several prototype engine designs dating to the 17th century. During this time, many scientists and engineers such as Thomas Savery and Christiaan Hyugens used hot gases and their pressure to operate pumps. At the turn of the 18th century, Thomas Newcomen attached a piston to his engine design. This allowed for pumping intervals, meaning it was able to produce continuous power. Despite its successful steps, the use of steam was still inefficient, resulting in unpredictable surges of power [4].

By the 19th century, significant progress was made in understanding the thermodynamics of combustion reactions. This led to the first commercially successful IC engine in 1859, invented by Étienne Lenoir.

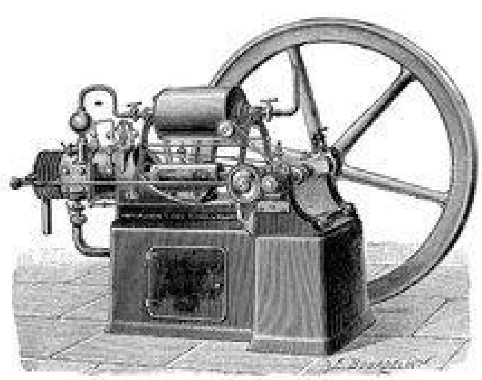

Figure 1. Lenoir gas engine, 1860 [5]

The Lenoir model employed new features that allowed continuous internal combustion to occur. For instance, a working cylinder was created with two pistons, wherein the slide valves would move the pistons up and down at alternating intervals. In Figure 2, this process allowed for a mixture of air and fuel to enter the open space (known as the combustion chamber) from one side of the piston where it would undergo combustion. At this step, Lenoir introduced the spark plug, a device that produces an electric spark, exploding the air-fuel mixture and thus, harnessing more energy. The energy is transmitted to an attached rod in the engine known as a crankshaft, rotating to drive the axles and thus, drive the wheels. Then, the pressure inside the combustion chamber forces the exhaust gases out through the slide valves on the opposite side. The large gear in Figure 1, also known as the flywheel, used a double-stroke to introduce air and fuel into the opposite side of the piston as soon as the spark plug was triggered so this process would repeat without delay, generating continuous power [6].

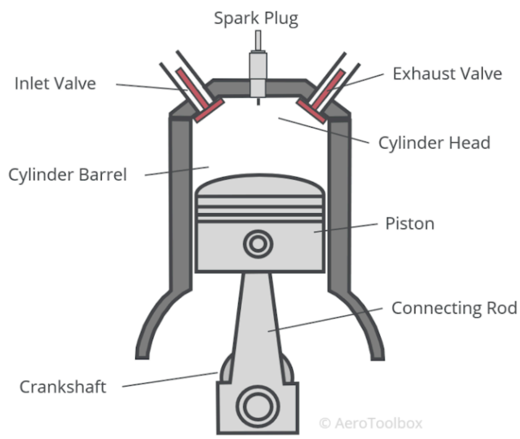

Figure 2. IC gasoline engine cylinder diagram [7]

In 1876, Nicolaus Otto built a four-stroke IC engine, a development from the Lenoir two-stroke engine. The two-stroke engine delivers power in two steps: the compression and power strokes of the piston. Contrarily, the four-stroke engine delivers power in four steps: intake, compression, combustion, and exhaust of the piston. The two-stroke engine fires once every cycle, while the four-stroke engine fires once every two cycles, both occurring when the piston reaches the top [7]. Typically, about 20% of fuel is converted from chemical to mechanical energy, while 5% is lost during energy conversion due to friction and other mechanisms. Although a two-stroke engine has a higher power-to-weight ratio, meaning it delivers more power while being lighter, it is not as maneuverable and requires more lubrication. Most importantly, the four-stroke engine was more fuel-efficient [8].

In terms of the ideal gas law, volume and pressure are inversely proportional. In Figure 3, at stage 1 (intake), the gas pressure is approximately atmospheric pressure, while the volume is at a maximum prior to piston movement. During stage 2 (compression), when the piston begins to move up inside the cylinder to create less space in the combustion chamber, the volume decreases, while the pressure increases. When the power stroke occurs in stage 3, the spark plug ignites, causing the explosion that results in maximum pressure (and temperature), while volume remains constant. As the gases exhaust in stage 4 and the piston moves down to create more space in the combustion chamber, the volume increases and the pressure decreases for this process to repeat [9].

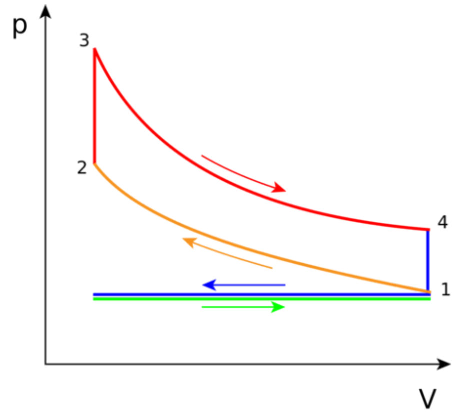

Figure 3. Ideal gas pressure–volume in combustion chamber of Otto cycle [9]

Soon, the IC engine was adapted to automobiles. In 1885, Karl Benz introduced a gas-powered single-cylinder four-stroke engine successfully adapted to the first ever car produced, known as the Benz Patent Motor Car. The engine was installed on the rear of the car and produced 0.75 horsepower (hp). Similar to the Otto engine, this engine featured the intake valve, exhaust valve, and a high-voltage spark plug. However, he also included a cooling mechanism for the engine using a water jacket and natural convection. As well, in 1897, he created the contra engine (or boxer engine), a two-cylinder engine with each on opposite sides of one another, producing 16 hp. Consequently, Benz later founded the first automotive brand, Mercedes-Benz [10].

Although gasoline engines were the first to be introduced into automobiles, Rudolf Diesel patented the diesel engine in 1892 [4]. Chemically, gasoline and diesel are both derived from crude oil. However, gasoline is a lighter fuel, whereas diesel is a heavier fuel and also has a higher boiling point. Fundamentally, gasoline and diesel engines were different in terms of the ignition stage. While a mixture of both air and fuel is injected into the combustion chamber at once in a gasoline engine, in a diesel engine, air is first compressed, then fuel is injected. As a result, the gasoline engine is commonly known as the "spark ignition engine", whereas the diesel engine is known as the "compression ignition engine" [11].

Throughout the years, IC engines also evolved to include subsystems and new components to improve efficiency, producing speed and agility as seen in motorsports. For instance, fuel injection, adapted from wartime airplanes, was introduced in 1955, wherein an electronically controlled system feeds gasoline into the combustion chamber the instant the engine is started. Prior to this, carburetors were used to mix air and fuel in proper amounts, ensuring combustion would occur [12]. Since carburetors were difficult to maintain and inefficient, they were swapped out for fuel injection, which also reduced power inconsistencies, stabilizing and improving the engine. Additionally, in 1962, turbocharging was added to the IC engine. Shaped like a snail, turbochargers restrict the flow of exhaust gases, leading to increased exhaust rates into the turbine and produce higher speed and torque [13].

Today, there are many different engine configurations and models from various manufacturers. Generally, a typical IC engine used in a five-seater sedan may look like the one shown in Figure 4.

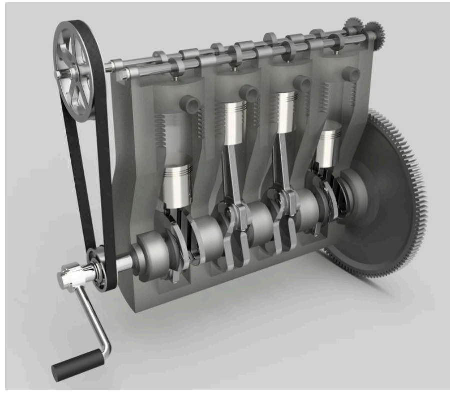

Figure 4. Inline-4 double overhead camshaft IC engine [14]

The engine above features four cylinders arranged in a straight line. At the top of the pistons, there are two camshafts. Camshafts are rods with cams (lobes shaped like a guitar pick) that, at certain intervals, open and close the intake and exhaust valves. The double overhead camshaft (DOHC) system allows one to be responsible for intake and the other for exhaust. One camshaft is attached to a gear that synchronizes camshaft movement and thus, allows for precise timing of intake and exhaust. It also helps move the crankshaft through a pulley system, reducing vibrations. Also seen in Figure 2, the crankshaft is attached to the pistons at the bottom via the connecting rods. It turns the large flywheel, which also ensures smooth power delivery to the transmission that helps control the speed delivered to the axles. The crankshaft and pistons are encased in a cylinder block, which also houses the air filter, oil pan, and other components [15]. Today, a typical engine like the type shown above, produces almost 200 hp [13].

Socioeconomic and Environmental Impact

The invention of the IC engine was pivotal to the rise of the Technological Revolution (also known as the Second Industrial Revolution) in the 1850s. The First Industrial Revolution occurred between 1760 to 1840 and was marked by the development of machine manufacturing. Following this, the Technological Revolution was characterized by the harnessing of electricity, gas, and oil as applicable to telecommunications, transportation, and mass manufacturing [16].

Most observably, the IC engine transformed transportation, allowing mobility freedom and access. Prior to its invention, horses and carriages were used for transportation, followed by trains which were powered by steam engines. However, with the introduction of the IC engine into compact vehicles, transportation could become personalized. They were also lightweight, durable, and high-speed, allowing people to travel faster and longer. In the United States, by the early 1920s, one in every ten people had an automobile [17]. The IC engine not only gave rise to road transportation, but also air transportation with the first airplane invented in 1903 by the Wright Brothers. This airplane was powered by a four-cylinder IC engine. By 1910, the airplane became publicly available both in the United States and in Western Europe, allowing cross-continental travel to be possible [18]. As a result, people could be self-reliant for work and travel, opening further opportunities for human exchange.

Additionally, the IC engine introduced a new industry: automotive manufacturing. For instance, after Henry Ford built his own car in 1896, he later founded the Ford Motor Company, which focused on assembly-line manufacturing, creating 40 000 employees in the Michigan factory. Ford also revolutionized the manufacturing process, replacing as much manual labour as possible with machines and tools. He also redesigned the workstation landscape of each operator including placing tools nearby and using conveyors as shown in Figure 5. As a result, more was produced in less time and using less resources, generating more revenue for the company. This in turn allowed the prices of vehicles to depreciate, making them more commercially available to a larger population. Specifically, the Ford Model T was priced at about $800 in 1910 and by 1924, it was sold at $300 each, which is equivalent to about $25 000 and $5000 adjusted to inflation respectively [16, 19].

Figure 5. Assembly line operators at the Ford automotive factory in 1913 Michigan [16]

Furthermore, the mass consumption of cars also gave rise to other industries such as oil and steel. As discussed, IC engines run on gasoline, which is made of crude oil that needs to be drilled, refined, stored, sold, and delivered to emerging gas stations. IC engines, along with car chassis, are made of different metals including steel, iron, and aluminum. Other materials like glass are also used for windows on cars. Hence, collecting and processing these raw materials created jobs. Prior to oil, people relied on coal, but with the invention of IC engines, a more efficient and relatively cleaner energy source compared to coal took over. This was especially the case in 1920s America across California, Oklahoma, and Texas [20]. Today, the oil industry is worth about $4 trillion in 2023 [21].

Consequently, the ability to travel in conjunction with the mass production of goods during this time opened up tourism and along with the adaptation of IC engines into cargo trucks, consumerism increased. As car ownership became more popular, outdoor leisure and cross-country travel brought about changes in landscape and businesses. For instance, the government contracted construction workers to build more roads, culminating in the Interstate Highway Act of 1956, which introduced the expansion of highways, making American urbanization possible. With holiday travel, hotels, souvenir boutiques, restaurants, and other services emerged [22]. As well, goods could now be shipped out and delivered faster, creating job opportunities such as drivers. No longer did items need to be sent through railways as companies could now have private delivery services. Specifically, this created more markets across longer distances, catering to different regional and at times, international needs for farmers, merchants, and industrialists [23].

However, though the invention of IC engines intended to eliminate manual labour and enhance mobility, they were also used in wartime vehicles that contributed to mass destruction. Shortly after IC engines were adapted to cars and planes, WWI occurred and saw a significant change in the waging of war, turning this technology into weapons. By 1916, soldiers were no longer riding horses into the battlefield, but they were riding on tanks powered by gas engines that cut through barbed wire and fired artillery [24]. As well, the use of IC engines in planes introduced a new military unit: air defense. Thus, more young men were recruited as pilots for bombers, attack helicopters, carrier-based strike airplanes, and fighter airplanes, while new tactics had to be devised including aerial surveillance [25]. With the advancement of technology in WWII, jet engines were developed, which were massive IC engines.

Furthermore, one of the biggest concerns with IC engines is its substantial effects on the environment. The burning of fuel such as gasoline and diesel releases carbon dioxide into the atmosphere which is classified as a greenhouse gas that traps heat, contributing to climate change. As well, if partial combustion occurs (incomplete combustion), deadly gases like carbon monoxide can be produced, which are considered toxins. It is important to note that along with byproducts released from IC engines, the extraction of crude oil also plays a role by releasing particulate matter such as soot and dust. All of this can cause vegetation damage, increased carcinogens, and air pollution. Over the last decade, the electrification of vehicle engines has been championed as the solution to this problem though significant advancements like turbocharging, alternative fuels, and toxin treatment systems were adapted to the IC engine. Thus, the push to purchase hybrid and electric cars increased [26].

Conclusion

The IC engine, though developed in the 19th century, was built on scientific and engineering principles through several centuries by many individuals, continuing to undergo transformations even today. As the world progressed through different ages, the IC engine was responsible for facilitating transportation, urbanization, and contributing to economic growth, demonstrating its versatility. Though the future of the IC engine is debatable, it stands as a cornerstone in powertrain technology, embodying the design lifecycle from its idea origin and evolution. It stands committed to responding to efficiency, emissions, and hybridization challenges in the present.

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