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Thermodynamic Limits and Chemical Energy Conversion Efficiency in Internal Combustion Engines

Bingjun Li[1, *]

[1]Middle School Affiliated to Beijing Normal University, Beijing, China
*Corresponding author: Libingjun_2020@outlook.com

Abstract:
Internal combustion engines remain critical for global energy conversion in transportation and heavy industry despite the rising share of renewable and electric power sources. However, their thermal efficiency is fundamentally limited by thermodynamic laws, and practical engines achieve only 25-40% efficiency due to irreversible processes such as friction, heat losses, incomplete combustion, and pumping losses. Additionally, these engines contribute significantly to pollutant emissions including CO_2, NO_x, and particulate matter, driving stringent regulatory pressures worldwide. This paper reviews the thermodynamic limits imposed by the Carnot cycle and the gap between ideal and real engine efficiencies, focusing on entropy generation caused by irreversibilities within the engine cycle. Key engineering challenges such as material thermal limitations, mechanical losses, and operational constraints are examined, highlighting the role of thermal barrier coatings, advanced cooling systems, and structural design improvements in mitigating these issues. Emerging technologies in fuel chemistry, including the use of Dimethyl Ether and high-octane synthetic fuels, alongside advanced combustion strategies like Homogeneous Charge Compression Ignition (HCCI) and Reactivity Controlled Compression Ignition (RCCI), demonstrate promising routes to enhance efficiency and reduce emissions. Furthermore, integrative system-level approaches combining ultra-high-pressure injection, low-temperature combustion, and thermoelectric generation offer future potential to break through current efficiency ceilings. This study underscores the necessity of collaborative advancements across structural design, fuel innovation, combustion control, and materials science to push the thermal efficiency of internal combustion engines closer to their theoretical limits, while simultaneously addressing environmental challenges.

Keywords: Internal Combustion Engine; Thermal Efficiency; Thermodynamic Limits.

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1. Introduction

Currently, global demand for energy is continuously rising, especially for transportation and heavy industry, in which internal combustion engines are still widely employed. Though the development of electrical and renewable energy causes the rising portion of the energy consumption, the internal combustion engine still accounts for a significant share of mechanical energy conversion worldwide. Unfortunately, internal combustion engines suffer from relatively lower efficiency, and their generation of greenhouse gas and pollutant emissions leads to higher pressure on the ecosystem. In fact, typical spark-ignition engines convert only 25-30% of the fuel's chemical energy to mechanical energy, and even in the diesel engine, the efficiency is still limited to 35-40% percent, and the remaining energy is lost primarily in several ways [1]. As, a result, the market share of internal combustion engine is huge, and its low efficiency strengthen the waste of energy worse.

The pollutants of the internal combustion engine include carbon dioxide (CO_2), nitrogen oxides (NO_x), and particular matter (PM). The concerns about these emission materials have been rising for several years, and are finally driving the promulgation of relevant policy in several regions in the world. In April 2024, the European Union stated the amendment of higher internal combustion engine pollution limitations over NO_x, PM, and CO pollution, and the introduction of new concepts about brake and type PM. Meanwhile, the US stated the Environmental Protection Agency Tier 4, which is seen as the strictest policy of pollution limitation, and focuses on the less emissions of PM and NOx. All of these show an increasing tendency that governments are considering pollution more, and the pressing need to improve the efficiency and lower carbon emissions.

Caron, in his study, states that the Carnot cycle limits the maximum thermal efficiency, which depends on the temperature of the heat addition and rejection process in the Carnot cycle. However, the ideal Otto efficiency of the gasoline engine and the Diesel engine is about 50-60% and 60-65%, much higher than the actual efficiency of these engines [2]. The huge differences between the ideal efficiency and actual efficiency are due to several contributions in the irreversible process inside the internal combustion engine, such as friction losses, coolant losses, and heat exhaustion. The difference represents a substantial room for improving the efficiency of the engine. As a result, to achieve higher fuel economy and reduce emissions, improving the thermal efficiency of internal combustion engines remains an important target for people. So, the main purpose of this research is to focus on methods of minimizing irreversibility and making the engine's efficiency closer to the practically attainable limit. This research will be divided into several aspects, such as structure, fuel, and materials.

2. Thermodynamic Principle and Practical Efficiency Constraints

2.1 The difference Between Ideal and Real Engine Cycle

The efficiency of the combustion engine is limited by thermodynamics itself. The ideal Otto and diesel engine cycle provides the possible theoretical efficiency limit, which is defined by the compression ratio and expansion ratio, as the following equation (1) shows.

$$\eta = 1 - TC / TH \tag{1}$$

In the equation, TC represents the absolute temperature of the sink, and TH represents the absolute temperature of the heat source. In fact, the actual process of the internal combustion engine is highly deflected from the theoretical process, which represents the Thermodynamic efficiency ceiling, and the efficiency limitation is much higher than the actual efficiency, which is led by some problems: the burning process cannot be completed immediately, the structure and time limit the expansion and change of gas, the pumping loss, and the parts of fuel cannot burn completely. All of these factors will cause the decline of efficiency.

2.2 Irreversibilities and entropy generation

The existence of irresponsibility in any real cycle of an internal combustion engine will cause the generation of entropy. This generation of entropy will lower the efficiency of a real engine, since the recovery of energy is reduced during the generation of entropy [2]. This generation of entropy plays a key role in lowering the efficiency of the engine.

The process in which heat from burning is transformed into the cylinder, piston, and coolant will inevitably lose some of the energy since the heat cannot be completely transformed. This will cause about 2-10% of energy to be wasted. The temperature of burning gas can reach about 2000-2700 K, much higher than the highest temperature that the metal structure inside the cylinder can withstand. SO some of the energy also has to be captured by the coolant to maintain the temperature inside the cylinder won't be too high and damage the inside structure. This will lead to the wasting of 20-25% of total energy. Furthermore, the friction between the piston, crankshaft, and camshaft also needs bearing resistance and pumping loss, which account for 5-10% of the total energy to be wasted. Meanwhile, conventional knock, which arises from the end-gas spontaneously autoignition, limits the achievable compression ratio, thus lowering overall efficiency. To avoid the problem of knocking, the designer of the engine has to control the compression ratio in a relatively low range. Though the exact data about the portion of energy being wasted caused by the effect of knocking is still unclear, there is an apparent result that the effect of knocking clearly causes a decrease in total efficiency. Altogether, all these irreversibilities significantly reduce the useful work generated by the internal combustion engine, and lead to it finally only containing about 30-40% of the energy that was left.

3. Engineering barriers to high efficiency

3.1 Material and thermal limitation

According to the equation I formally mentioned, the TH (burning temperature) count for a positive effect on the efficiency of the engine; however, the structure and mechanical pieces are resistant to a relatively low temperature, and limit the temperature value from being as high as possible. During the high-load operation of the diesel engine, the normalized temperature relative to the melting point can reach 0.8-0.9, and in this temperature range, the high-temperature mechanical strength, material instability will be significantly reduced, accelerated creep, and shortened 5 [3]. The strength of the material will decline with increasing temperature, causing the structure to be damaged, and thus, the temperature has to be limited to a relatively low range, which represents a lower efficiency. For example, the highest temperature of the surface of the piston is 301°C, many of which are made of Al-Si alloy or Al-Cu-Mg, and their melting temperature range is about 500-600°C [4]. The temperature is quite low compared to the temperature of burning gas. Since it is directly attached to the burning gas, the temperature it can tolerate limits the functioning temperature, and limits the highest T_H, and finally causes a low Carnot efficiency.

The structure with the piston and the valve will suffer thermal fatigue, caused by exposure to high temperatures for a long time. It may even lead to the formation of cracks after extension and compression. High temperatures will also induce creep deformation, especially when structures are operating in the yield point for long periods. Also, high temperature will weaken the protective layer on the surface of metal, oxidize the surface, or even cause surface ablation. Creep failure modes, thermal fatigue, and oxidation of bond coat and substrate are all contained in the couple of failure modes. Research has been done to solve this problem, which is called thermal Barrier Coating (TBC). This technology can drastically extend the usage period, especially on gas turbine or a high-load combustion engine; however, spallation may occur if the Interfacial bond strength decreases with thermal cycling. The TBC is focused on solving the problem associated with the metal structure that cannot withstand extremely high-temperature conditions. The average temperature of metal structures can decline by about 100-150°C, which can reduce the effect of thermal fatigue and thermal impulsion. TBC does play a crucial role on solving the problem led by internal combustion engine thermal limitation [5].

To avoid the temperature won't be too high, the engine requires a cooling system, which contains coolant, fans, and a water pump. But this system will spontaneously introduce parasite losses, since the heat is wasted passing through the cooling system. In high-load operation, this source of energy loss can reach 5-8% of total input energy. To avoid the hot spots' damage around the oil pump. A modern diesel engine will be designed with multiple points designed for refined cooling channels, which will further complicate the cooling system, increase the pump work, and require a higher compact structure and pump efficiency [6]. Overall, the cooling system leads clear decrease in total energy, but it cannot be simply removed caused to the thermal limitation of the metal structure.

3.2 Mechanical and operational losses

Although the heat source temperature and material have already gained improvement, the internal structure of the internal combustion engine still contains a large amount of energy waste. These losses of energy are mainly caused by friction, pump losses, and transmission accessories.

About the pumping loss, a low-load operating internal combustion engine, when a family-use vehicle operates in the city, can generate a pumping loss. In a spark-ignition engine, part of the throttle valve will be closed, creating intake manifold vacuum, and this causes the pumping loss to bring the gas exchange process, since the vacuum requires a higher amount of useless work to be done. The throttle causes the generation of a vacuum, and thus generates pumping loss; this loss relative to the indicated work can account for about 25-30%, significantly reducing the efficiency [7]. Although a diesel engine does not have the structure of a throttle valve, which means it won't have to face the problem related to the formal paragraph mentioned, the higher rate of exhaust gas recirculation (EGR) rate will cause the exhaust back pressure

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to increase, which also generates the pumping loss, which relatively accounts for 12-18% of indicate work.

The movement of the piston, cylinder liner, crankshaft, cam, and other moving parts will inevitably suffer friction during the operation process. As the speed becomes higher, the friction will also increase drastically. Furthermore, accessories such as water pumps, oil pumps, and air conditioning compressors consume engine output power; this loss of energy is called parasitic and can account for about 5-10% of total energy input.

The losses led by function cannot be completely eliminated, and a higher efficiency engine must improve in collaborative structure, optimization of lubrication, and control. The following chapter will discuss several research studies to solve these associated problems.

4. Pathways Toward Efficiency Enhancement

4.1 Structural Innovations

A possible way to decrease irreversibility, which represents pumping loss and friction loss, is to optimize the structure of the internal combustion engine. There are several technologies:

Firstly, the variable valve timing (VVT) technology reduces the pumping loss through moderating the timing of the intake and exhaust stroke opening. Secondly, by delaying the timing of the intake stroke close, the Atkinson cycle/ Miller cycle can reduce the compression ratio and improve the total efficiency. Thirdly, the warmth heat recapture can recycle the heat contained in higher-temperature exhaust gas. This technology can increase the overall 5% of total efficiency, and gas is already being used in some commercial vehicles.

4.2 Fuel Chemistry and Combustion

The characteristic determines the burning process and efficiency. Different materials can lead to a drastic change in total efficiency. For example, the difference between Dimethyl Ether and conventional fuel of diesel engine. The Dimethyl Ether has a lower delay in ignition, more suitable for homogeneous charge compression ignition (HCCI), and this represents a better reactivity [8]. Also, high-octane synthetic fuel shares a relative advantage compared to conventional fuel. In Wu's research, high-octane synthetic fuel shows a drastically high performance in a spark ignition engine. All these show that the material is an important is an important way of improving the total energy, and has already achieve many improvements.

4.3 Advanced Combustion Strategies

The homogeneous charge compression ignition (HCCI) and the reactivity controlled compression ignition (RCCI) are two systems that depend on compression of fuel and fuel stratified injection, to achieve a higher uniform and thermal efficiency. Technology about HCCL has achieved a low emission of NO_X, and a higher thermal efficiency, but does require a more complicated system for manipulating the engine [9]. Meanwhile, new ignition technologies have also been invented, and have broken through the limitations of the conventional spark plug in lean burn. According to Li's research, this technology can delay knocking, which is beneficial to lean burn [10].

5. Emerging Technologies and Interaction Outlook

Conventional thermal efficiency has already approached the limitation; further research should focus on integration breakthroughs. There are three types of advanced technology.

First of all, the ultra-high-pressure injection technology can improve the atomization of fuel and shorten the burning period. The second one is the Low-Temperature Combustion, which manipulates the temperature of burning fuel in a relatively low region (lower than 1800 K) and inhibits the generation of NO_X, and improves the mixture of fuel and achieving a cleaner burning, but this requires a highly complicated control system. The third one is the thermoelectric generator, which can implicit the energy of high-temperature exhaust gas, and use this energy to drive the operation of electronic devices in the vehicle.

In the future, advanced innovation should consider integrative technology, instead of existing independently. Integrative technology is an important way to optimize the system level. Researchers should mix different dimensions, such as structure, material. burning, and control, and this is an important way to optimize the system level.

6. Conclusion

The efficiency of the internal combustion engine is fundamentally limited by several key factors: thermal irreversibility, material temperature limitation, friction, and pumping air. The current advanced technological innovations do improve the efficiency of the engine, but the marginal return on higher efficiency is diminishing, and cannot be effectively improved with simple structural and burning improvements, and requires more integrative innovation.

In future research, the direction should be more focused on cross-dimensional collaboration, including material, burning, control, and exhaust gas recollection. To achieve the goal of carbon neutral, internal combustion engine is more likely to retain their role in two ways: The Hybridized with electric drives to form "high-efficiency, long-range systems" (such as plug-in hybrid electric vehicles), and transforming into "carbon-neutral power sources" using zero-carbon synthetic fuels (such as ammonia and e-fuel).

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