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REVIEW OF IMPROVEMENT METHODS OF INTERNAL COMBUSTION ENGINE EFFICIENCY

Noureddine Guellouh [1]***, Zoltán Szamosi*** [2]***, Zoltán Simenfalvi*** [3]

[1] PhD student, [2] Assistant Professor, [3] Associate Professor
[1, 2, 3] *Institute of Energy Engineering and Chemical Machinery, Faculty of Mechanical Engineering and Informatics, University of Miskolc, Miskolc, Hungary*
[1] *vegynourg@uni-miskolc.hu*, [2] *vegyszam@uni-miskolc.hu*, [3] *simenfalvi@uni-miskolc.hu*

ABSTRACT

Internal combustion (IC) engines are the most preferred option for automotive powertrain. Two commonly used engine types are spark ignition and compression ignition engines. The stringent emission regulations motivate researchers to improve IC engine performance to increase efficiency and reduce emission levels. There are many factors that limit IC engines efficiency, for example heat losses, losses due to incomplete and imperfect combustion, heat losses during cooling, imperfect valve timing, etc. In this paper, a comprehensive review of the most common and compromising methods and technologies that can be used to optimize the IC engines efficiency is represented.

KEYWORDS: internal combustion engine, improvement method, efficiency

1. INTRODUCTION

It is well known that the internal combustion engine is considered as an engine in which the chemical energy of a specific kind of fuel is released inside the engine and used directly to get mechanical work, as opposed to an external combustion engine type in which a separate combustor is used to burn the fuel [1]. IC engines have been one of the most important energy conversion technologies. They have been used to power transportation devices and produce electricity around the world for more than hundred years [2]. They were initially used as stationary engines, but then, they started also being used in vehicles thanks to their characteristics especially their high power-to-weight ratio [3,4]. Compression Ignition (CI) or Diesel engines and Spark Ignition (SI) engines which are known as petrol or gasoline engines are the main technologies, which have reputed and established applications in the automotive sector [5], where almost all 95% of the world's transportation energy comes from petroleum-based fuels (largely gasoline and diesel) [6]. Both gasoline and diesel engines can consume and operate on either a liquid or gaseous type fuel. The heat that is released as the fuel burns within the combustion chamber creates high-pressure expanding gases that are converted to mechanical energy as they force the piston down the cylinder to rotate the engine crankshaft. The stringent regulations governing greenhouse gases (GHGs) emissions especially Carbon dioxide (CO_2), Nitrogen Oxide (NO_x), Methane (CH_4), etc, and Particulate Matter (PM) emissions and higher fuel price have demanded cleaner combustion and increased fuel efficiency from the internal combustion engines, where the desire to increase fuel efficiency of these engines while simultaneously meeting emissions mandates has motivated considerable research [7].

2. THERMODYNAMIC REQUIREMENTS FOR MAXIMUM INTERNAL COMBUSTION ENGINE EFFICIENCIES

The development of high efficiency, low emission ICEs is one of the most important issues nowadays in combustion technology research, this is why scientists and engineers are seeking to achieve this goal through different experiments and researches. Knowledge of the actual maximum

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possible efficiencies is a very important aspect of this development, where the thermodynamic limitation for the maximum efficiencies of ICEs plays a key role in the design and development of future engines.

In thermodynamics, compression ratio, heat transfer, lean mixtures, combustion irreversibilities, mechanical friction, ratio of specific heats and burn duration represent the main factors that affect the thermal efficiency, in addition effect of engine size [8]. Regarding the compression ratio, high compression ratios are an important engine design parameter for high efficiency, where previous studies have shown that the maximum efficiencies were about 62% and 67% for compression ratios of 20 and 30 respectively (no heat loss and no mechanical friction as initial conditions), but the destruction of exergy during the combustion process for these two cases was about 28% and 26%, respectively. So the main reason that the maximum thermal efficiencies cannot be closer to 100% is this exergy destruction. Also, the thermal efficiencies can be increased by reducing cylinder heat transfer, which is difficult to be achieved and even for reduced cylinder heat transfer, the increases of work are small or zero due to the difficulties of converting thermal energy to work. The use of lean mixtures is very useful because it results in lower combustion temperatures, these lower temperatures lead to less heat loss and higher ratios of the specific heats, but higher inlet and cylinder pressures are needed to achieve the required load. The maximum possible thermal efficiency for ICEs even with no heat losses or friction is limited by the combustion irreversibilities knowing that combustion irreversibilities are not related to incomplete combustion, they are due largely to the chemical reactions, mixing associated with combustion processes and heat transfer. Many researches [9,10,11,12] have been completed to investigate the possibilities to minimize these irreversibilities. Within the constraints of typical engines, no feasible approach has been identified. [12] has shown that even if the irreversibilities could be reduced, the preserved exergy would not result in much if any additional work. The preserved exergy, however, would remain in the exhaust. Reducing mechanical friction as much as possible is one of the most important goals of engine manufacturers, where reductions of mechanical friction translate directly to increased brake work. The thermal efficiencies during combustion process can be increased in case of higher values of the ratios of specific heats. On burn duration, short durations provide higher thermal efficiencies largely due to the more effective expansion work, but higher peak cylinder pressures, higher pressure rise rates and increased engine noise are some disadvantages of using short burn durations.

The size of engine is one of the items that affect the maximum possible efficiencies because the cylinder surface area and volume ratio which typically decreases as the engine size increases. This result in less relative heat loss if all else is the same. As engine size increases, the surface area and volume ratio rapidly decrease, the relative cylinder heat transfer decreases (due largely to the decrease of the surface area and volume ratio) and the net indicated thermal efficiency increases largely due to the reduction of the relative cylinder heat transfer. Only a fraction of the energy retained due to the decrease of the relative cylinder heat transfer, however, converts to work. The remaining energy remains in the exhaust gases [8].

3. METHODS AND TECHNIQUES TO IMPROVE THE EFFICIENCY OF INTERNAL COMBUSTION ENGINES

Failure to achieve high levels of combustion efficiency is generally regarded as unacceptable, partly because combustion inefficiency represents a waste of fuel, but mainly because it is manifested in the form of pollutant emissions like unburned hydrocarbons and carbon monoxide. That is why current emissions regulations call for higher combustion efficiencies.

Inside ICEs, the fuel chemical energy is converted to vehicle kinetic energy through specific thermodynamic cycles, but not all the fuel’s energy can be converted into vehicle movement. Basically, the combustion efficiency of these types of engines can be defined as the proportion of fuel energy that gets transmitted to indicated work, or in other words, the work that the high-pressure in-cylinder gases do to the pistons during an engine’s power stroke. The efficiency of ICEs is limited because of several factors such heat losses in exhaust gases, losses due to incomplete and imperfect combustion, heat losses during cooling of engine, imperfect valve timing, losses in driving cam shafts, energy consumed by auxiliaries like water pumps and oil pumps, etc. This is why many research and experiments are done to figure out how to minimize these losses to achieve higher efficiency. Thanks to the desire to achieve high engine efficiency and the great developments in computer-aided design and simulation, a rapid technology improvement has been achieved to reduce the sources of energy loss.

3.1. TURBOCHARGER AND SUPERCHARGER

The use of turbochargers and superchargers in modern internal combustion engines is very common. They are mounted in the intake system to raise the pressure of the incoming air [13].

A turbocharger is a turbine-driven forced induction device, it consists of turbine and compressor coupled to a common shaft. It uses exhaust energy to produce useful boost for engine intake, where the exhaust flow from the engine is used to spin a turbine which in turn spins an air pump (compressor), this will raise the pressure of air or air fuel mixture that is to be supplied to combustion chamber (inside the cylinder). The potential of higher power with turbocharging leads to engine downsizing to improve fuel economy while maintaining driving performance [14]. Turbocharged engines do not suffer a dramatic reduction in power since the turbocharger is more capable of pumping thinner air, and they are effective at high altitudes. The process of matching a turbocharger to an engine is very important in the early stages of design, where air system simulations are needed. According to many research, further increase in the reliability of turbochargers can be achieved thanks to advanced manufacturing technologies and design changes: integrated correctors for fuel supply can cause a reliability increase up to 10-25%, the modernization of the ICE lubrication system up to 5-7%, bearing assembly improvements up to 15-20%, the use of new structural materials up to 10-13%, the reduced vibration of the turbocharger elements up to 2-5%, the heat removal improvement from the turbocharger case up to 10-20%, the reduced thermal factor of the turbocharger elements up to 5-10%. According to practical application of turbocharged engines, the wear resistance factor of the bearing assembly is considered as the main indicator of their reliability. Also, the shaft (rotor) seizure is known as the most common failure of turbochargers [15].

The supercharger is also known as forced induction system. The source of the power for this device is in a belt connected directly to the engine. It does the same work as that of the compressor, where it compresses the air (from the atmosphere) being delivered to the combustion chamber. The greater mass flow-rate provides more oxygen to support combustion process than would be available in a naturally-aspirated engine, this allows more fuel to be added, therefore more work and more power can be achieved from each explosion in each cylinder [16]. In general, supercharging has a significant effect on the power output because it is possible to get higher values compared the naturally aspirated engines thanks to several reasons: higher amount of air in the intake system, the mechanical efficiency is slightly improved, some of the work done on the supercharger is recovered during the gas exchange process, better scavenging and reduced exhaust gas temperature in the engine can be achieved due to supercharging and the reduced residual gas fraction helps in better combustion and reduced temperature improve volumetric efficiency [17].

Basically, the power output of an engine is limited by knock, thermal and mechanical loads. Usually one of these limits is reached earlier than the other limits depending upon the type of engine and its design of the structure, the cooling arrangements, etc. In case of SI engines, the degree of supercharging is chiefly limited by the knock (knock limit is usually reached first in SI engines). The increased pressure and temperature due to supercharging reduces ignition delay and consequently the engine has a knocking tendency at these pressure, knowing that knock limit is dependent upon the type of fuel used, mixture ratio, spark advance and the design features of the engine, etc [18]. In case of IC engines, the limit of supercharging is reached by thermal loading. Unlike SI engines, the limits of supercharging for compression-ignition engines are not due to combustion. The factor which limits the power output of a SI engine due to knock, results in quieter and smoother operation of a CI engine. The increase in pressure and temperature lead to decrease the ignition delay and engine runs smoother [18].

3.2. DIRECT FUEL INJECTION

Fuel injection system has been one of the most important issues in the development of ICEs for many years and has been refined many times over the decades. The manufacturers began to replace carburetors with electronic fuel injection (EFI) systems since 1980s. Many of the early EFI systems were throttle body injection (TBI) systems that sprayed fuel from one or two injectors into the intake manifold (the fuel was injected above the throttle plates), much like carburetor had done previously, but with much more accuracy. The major drawback was the use of the intake manifold to supply fuel to each cylinder. Port fuel injection (PFI) system sprays fuel just behind the intake valve, which prevents fuel from condensing in the manifold and has eliminated the need for a heated intake. Earlier port fuel systems were multiport fuel injection (MFI), and injected fuel was bank fired, first firing half the injectors, and then the other half in 180 degrees of crank rotation regardless of intake valve position. Sequential fuel injection was a port fuel injection system that delivered fuel when the intake valve was opening for a more accurate delivery, and some fuel mileage and idle performance gains were also realized [19,20]. The latest fuel injection system is direct fuel injection (DFI), where the fuel is fuel is injected directly into the combustion chamber (inside the cylinder) at very high pressures and the combustible mixture formation takes place almost exclusively in the combustion chamber [21]. The DFI allows gasoline and diesel engines to burn less fuel and gives precise control over the timing and the amount of fuel which is injected. The use of this system provides better cylinder charging, higher compression ratio, reduced knock sensitivity, higher pressure stratified charge injection at start-up, multiple fuel-injection, etc. In general, the use of this type of fuel injection system provides lean burns as well as increased engine performance, fuel economy and reduced emissions levels. The DFI system poses some challenges, especially with regard to the complexity, the cost and the components (fuel injectors) must be able to withstand the high heat and pressure of combustion inside the cylinder [22].

3.3. VARIABLE VALVE TIMING

The variable valve timing (VVT) technology has a very obvious effect on the gas exchange process of engine, which in turn influences the engine performance and cylinder charge properties [23], such as pumping loss, residual gas fraction RGF, density of charge and unburned gas temperature, volumetric efficiency, and finally determines the engine performance [24].

The VVT system is a term that is used to describe a vast array of different valvetrain changing type systems. These systems have added components that allow the intake or exhaust valves (or both) to change the lift, duration, or timing during operation of the IC engine [25]. Changing valve timing in response to driving conditions provides many advantages, where it improves driveability and lowers fuel consumption and emission levels can be achieved [26].

There are three major types of VVT: intake cam phasing (ICP), coupled cam phasing (CCP) and dual cam phasing (DCP). The cam phasing, which changes the phase angle of the camshaft with respect to the crankshaft, is the widely used form of VVT nowadays. CCP and DCP can modify the timing of both the inlet valves and the exhaust valves, but DCP is the most flexible design, controlling intake and exhaust valves independently [27]. Most staged systems of VVT allow two different valve timing and lift settings. Continuously variable systems alter valve timing whenever operating conditions change. Continuously variable systems change the phasing or timing of a valve's duration. A wider torque curve, reduction in fuel consumption, improved power at high speeds, and a reduction in hydrocarbon and nitrogen oxide emissions, can be provided by using these systems [26].

The mechanisms that allow valves to change their behavior are almost as numerous as there are manufacturers of engines. For example, Sequential Valve Timing (S-VT) used by Mazda, Nissan Variable Timing control (N-VCT), Variable Camshaft Timing (VCT) used by Ford and Yamaha, Variable Valve Timing and Lift Electronic Control (VTEC) used by Honda, VarioCam and VANOS technologies used by Porsche and BMW successively, etc.

3.4. VARIABLE COMPRESSION RATIO

The concept of variable compression ratio (VCR) promises improved engine performance, efficiency, and reduced emissions [28]. It has been observed that a fixed compression ratio engine cannot meet the various requirements of high specific output. Hence, the development of variable compression ratio engine seems to be a necessity and a good solution [29]. VCR is the technology to adjust internal combustion engine cylinder compression ratios to increase fuel efficiency under varying loads [30]. Where, this technology increases the compression ratio at low engine load to promote thermal efficiency, and it decreases the compression ratio at high load to reduce knock risk and improve engine performance. VCR engines change the volume above the piston at top dead center. The change is done dynamically in response to the load and driving demands. As turbochargers are used to specific output of downsize engines, VCR becomes more desirable as an enabler for even higher boost pressures. Since some changes in effective compression ratio can be achieved with VVT, the improvements that might be obtained with VCR may be diminished [31].

The VCR can be used for both SI and CI engines. However, the concept of this technology can be more suitably used with turbocharged diesel (CI) engine because of two main reasons. The first reason is that the concept of VCR is beneficial only at part load and the part-load efficiency of the diesel engine is higher compared to that of the gasoline (SI) engine. The second reason is that the diesel engine has better multi-fuel capacity [32]. Therefore, a VCR can generally be used for SI and CI type engines, but some major modifications of the basic engine or of engine components are required. Some of the feasible engine concepts are: auxiliary chamber in cylinder head, piston with variable compression height, vertically sliding cylinder head, adjustable connecting rod length, eccentric main crankshaft bearings, etc [33].

3.5. COOLED EXHAUST GAS RECIRCULATION

The use of Exhaust Gas Recirculation (EGR) has been in use to reduce emissions and to enhance engine, performance**.** It is commonly used on diesel engines. Globally, its employment to meet emissions requirements is growing. EGR re-introduces a portion of the exhaust normally emitted by the vehicle and uses it as part of the fresh air intake air to provide inert mass in the cylinder to reduce peak flame combustion temperature, and thereby reduce NOx emissions. EGR can be achieved by several ways. The internal EGR (hot EGR) represents a simple way, whereby some of the exhaust is retained in the cylinder or leaked into the fresh air charge while it is being inducted. However, internal EGR is not cooled and, therefore, the NO_xreduction is relatively small compared to external EGR (cooled EGR) which allows the recirculated exhaust gas to be cooled as it flows through a pipe, or more aggressively by a heat exchanger using engine coolant or cooling air. Therefore, because of the ability of cooled EGR to limit more NO_x effectively, and larger amounts of EGR can be used without displacing as much air, this method has become a very common method of NO_x emission control in IC engines [34,30].

In cooled EGR the exhaust gases are cooled and then diverted through the intake manifold into the cylinders along with filtered air and air from the outside of the vehicle by using of a variable geometry turbocharger, so as to balance the fresh air/EGR ratio.

Cooling the exhaust before mixing it with the intake stream further exploits this technology’s potential for improving engine efficiency. Cooled EGR also reduces fuel consumption by decreasing fuel enrichment, which is used to reduce exhaust gas temperature at high engine loads.

On turbocharged engines, the lower combustion temperature also results in higher turbo pressures and higher engine output, enabling further engine downsizing and downspeeding. The addition of inert exhaust gas to the intake system means that for a given power output, the throttle needs to be opened further, thereby reducing pumping losses at low engine loads [27].

3.6. WATER INJECTION

Water injection is considered as an advanced technique that relies on injecting fine spray of water into the intake port. This method is viewed as one of the possible solution for many problems in internal combustion engines since it promises to make the engine operating with larger compression ratios and stoichiometric combustions at high load, resulting in a drop of the specific fuel consumption on the overall engine map [35]. Many studies have been conducted by various researchers to investigate the effect of water injection on the performances of IC engines, where they found that by using this technique the risk of knocking can be reduced, thus enabling higher compression ratio through charge cooling by the evaporation of water in the engine's cylinders. Also, fuel efficiency can be increased by reducing heat losses and fuel enrichment, and it allows the engine to operate with higher boost and earlier spark timing, resulting in greater power and torque [27]. In general, 13%-20% reduction in fuel consumption at high loads and a 4%-6% reduction over an entire drive cycle (New European Driving Cycle (NEDC) or Worldwide Harmonised Light Vehicle Test Procedure (WLTP)) can be achieved with water injection technique.

Coupling water injection with VCR and cooled EGR technologies provides very good results and characteristics, where VCR can compensate for higher knock limitations with a lower compression ratio if water injection cannot be used due to a lack of water or at low ambient temperatures. At the same time, high compression ratio can be maintained up to the highest loads if water injection is possible. The amount of injected water can be reduced with the use of cooled EGR.

The application of water injection is faced with several challenges that must be investigated, for example minimizing water consumption is an obstacle where most studies indicate an optimum water to-fuel ratio of 30%-50%, which translates to 2.4-3.9L/100 km of water consumption for a vehicle with fuel efficiency of 7.8 L/100km, this would require filling up a 10L water tank at roughly every other fuel stop. Minimizing costs, improving reliability of injection systems, minimizing lubricant contamination, verifying its compatibility with cold climate temperatures are also some important issues that must take into consideration for future studies.

3.7. LOW TEMPERATURE COMBUSTION

The stringent emissions regulations guide research to improve IC engine performance with higher efficiency and lower emission levels. Low temperature combustion (LTC) engines have potential to deliver higher fuel conversion efficiency and simultaneous reduction of NO_x and soot emissions to an ultralow level. The LTC engines can also reduce the heavy dependence on NO_x and soot after-treatment devices for meeting the emission norms [36]. However, controlling ignition timing and heat release rate (HRR) are important challenges for the use of LTC technology in IC engines [5].

Basically, the success of LTC technology depends on the following main steps: preparation of a highly dilute fuel-air mixture using EGR to control combustion and the heat release rate. At the end of compression stroke, fuel-air mixture temperature approaches auto-ignition temperature, leading to simultaneous spontaneous ignition of entire charge in the cylinder at several locations. And finally, precise control of heat release rate (HRR) to achieve trade-off between combustion efficiency and emissions.

The technology of LTC could be achieved by adopting various strategies including Premixed Charge Compression Ignition (PCCI), Reactivity Controlled Compression Ignition (RCCI), High Efficiency Clean Combustion (HECC), Homogenous Charge Compression Ignition (HCCI) and Stratified Charge Compression Ignition (SCCI) [37].

LTC technology provides several advantages, among them: LTC approximates a constant volumetric combustion in very short combustion duration, and it can be achieved for high compression ratio, therefore, it results in higher thermal efficiency. Relatively lower peak combustion temperature leads to better energy utilization due to lower radiation losses. Throttling losses are also absent in comparison to a SI engine. Another important advantage of LTC is its fuel flexibility (gasoline, mineral diesel, biodiesel, alcohols, etc). Also, LTC engines are suitable for the replacement of conventional SI and CI engines. These engines can also be coupled with advanced hybrid engines, i.e., to combine the advantages of highly efficient IC engines with electrical series hybrid powertrains [5].

3.8. HOMOGENEOUS CHARGE COMPRESSION IGNITION

The Homogeneous Charge Compression Ignition (HCCI) is a promising technology for the development of IC engines especially with regard to low emissions of Nitrogen Oxides NOx and soot and high volumetric efficiency. HCCI can be achieved by premixing the air-fuel mixture (either in the manifold or by early Direct Injection (DI) -like in a SI engine) and compressing it until the temperature is high enough for autoignition to occur (like in a CI engine) [38].

A significant fuel economy benefits can be achieved by using HCCI technology, due to a combination of highly lean operation and a resulting high specific heat ratio and reduced pumping losses, typically higher compression ratio, and shorter combustion duration [27]. However, this technology is not without problems and challenges, since carbon monoxide emissions levels and unburned hydrocarbons emitted from HCCI engines are usually higher than the corresponding ones of conventional engines [39]. Moreover, controlling the ignition timing and combustion rate is extremely challenging [39]. Also, it is difficult to prevent explosive combustion at high engine loads due to excessive dense fuel and to prevent misfire at low engine loads. Thus, the operating range of conventional HCCI is has been limited to a small region on the engine map [27].

To achieve dynamic operation in an HCCI engine, the control system must change the conditions that induce combustion. Thus, the engine must control the compression ratio, inducted gas pressure and temperature, fuel-air ratio or quantity of retained or reinducted exhaust [33].

In general, there are many advantages that HCCI technology can offer for engines manufacturers, these advantages can be summarized in as follow: it provides up to 30% fuel saving while meeting current emissions standards. Since HCCI engines are fuel-lean, they can operate at a diesel-like compression ratio, thus achieving higher efficiencies from conventional SI gasoline engines. HCCI engines can operate on gasoline, diesel and most alternative fuels. Homogeneous mixing of fuel and air leads to lower emissions, where since the lower peak temperatures compared to other engines, the NO_x emissions are almost negligible. In addition, the premixed lean mixture does not produce soot. Compared to SI engines, the absence of throttle losses improves HCCI efficiency. In HCCI, the entire reactant mixture ignites almost simultaneously. Since very little or no pressure differences exist between the different the different regions of the gas, there is no shock wave propagation and hence no knocking [33].

4. CONCLUSION

Significant efforts by researchers to develop the efficiency of IC engines have led to the development of new technologies that have demonstrated an ability to achieve better efficiency, lower emissions and better performance. For example, the use of turbochargers and superchargers, direct fuel injection, variable valve timing, variable compression ratio, exhaust gas recirculation, water injection, low temperature combustion, homogeneous charge compression ignition, etc. All these methods have shown effective results in improving the efficiency of ICEs, but there are still many challenges relate to how to make them more suitable for IC engine characteristics. Also, there is a need to improve these methods to achieve much higher efficiencies, by investigating the effect of changing designs and concepts of these methods, or studying the possibilities of combining the concepts of several methods.

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