Combustion Efficiency Enhancement Techniques in Modern Diesel Engines

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Abstract:
Combustion efficiency The ratio of the chemical energy of diesel fuel that is discharged and transformed into useful work is a key lever that is being used to drive modern compression-ignition engines to greater brake thermal efficiency (BTE). Although the highest possible BTE has been demonstrated at the range of 43-45% with heavy-duty diesel engines, research programs and technology demonstrators have indicated that higher gains can be obtained when combustion completeness, phasing of heat-release, and mixing of air and fuel are optimized together through mechanical innovations. The present paper summarizes the PhD-level evidence on the major mechanical methods of improving diesel engines in terms of combustion-efficiency, focusing on fuel-injection and air-management equipment. Topics covered in the review include: (i) high-pressure common-rail injection and enhanced rate-shaping/multiple-injection strategies to enhance atomization, shorten ignition delay, and reduce over-rich zones; (ii) enhancements to architectures (variable geometry turbocharging, two-stage turbocharging with intercooling, and turbo-compounding) to augment excess-air supply and recover exhaust enthalpy; (iii) optimization of combustion-chamber and intake-flow (piston bowl geometry, port design, swirl In all these methods, the key efficiency enhancement tool is the redistribution of heat release to higher levels of effective pressure, and the reduction of incomplete combustion losses (CO, HC, soot precursors) and the occurrence of late-cycle burning. Nevertheless, the review also mentions some major limitations, in particular, the formation of NOx, peak cylinder pressure restrictions, parasitic losses in high-pressure pumping and boosting, and extreme pressures and high-temperature material issues. The general finding is that the most practical gains can be made by system-level integration (injection + air system + chamber design + valve strategy) in line with the high-efficiency demonstration programs which have shown that with well-coordinated mechanical upgrades BTE can now reach or exceed 50% of its under-optimized operating conditions (Dahham et al., 2022; Mohan et al., 2013).

Keywords: diesel combustion efficiency, brake thermal efficiency, high-pressure common rail, multiple injection, turbocharging, variable geometry turbocharger, two-stage boosting, intercooling.

Introduction

Diesel engines are known to be incredibly high fuel efficiency where a significant percentage of the fuel energy is converted into work. In present practice, the highest thermal efficiency (BTE) of internal combustion engines is around 43-45% in heavy-duty diesel engines, and this is the most efficient engine. This total efficiency is a product of several factors - combustion efficiency (the degree to which the chemical energy in the fuel is released), thermodynamic cycle efficiency, gas exchange efficiency and mechanical efficiency. The efficiency of combustion in specific terms is the extent to which fuel is completely burnt in the cylinder, anything that is not burnt or partially combusted is unused energy. Engineers and researchers have over the decades come up with a number of mechanical methods of improving the efficiency of combustion and thus improving the BTE. These are high-tech fuel injection systems, boosting (turbocharging/supercharging) systems, improved in-cylinder air movement, and other design developments. The paper is a review of mechanical methods of enhancing the combustion efficiency of modern-day diesel engines with reference to the fuel injection and air management methods at a PhD level depth. In-text citations are taken in the short form (Author, Year), and the references are given in full in APA style in the References section.

The major mechanical approaches that have been dealt with are: high-pressure common rail fuel injection (to enhance the atomization and mixing of fuel), multiple injection timing (to regulate the timing and duration of combustion), turbocharging (single and multi-stage, including variable geometry and turbo-compounding, to boost air charge and recover exhaust energy), combustion chamber structure optimizations (piston bowl shape, and intake port geometry to induce swirl/tumble to enhance mixing), variable valve actuation (Miller cycle) to optimally enhance expansion ratio, and low- Such trade-offs include impacts on emissions (e.g. NOx formation) and feasibility of each method. It is aimed to point out how these mechanical inventions improve the in-cylinder combustion process resulting in a greater degree of fuel burn and greater engine efficiency.

High-Pressure Fuel Injection Systems

The high-pressure common rail fuel injection is one of the most effective developments that have influenced the efficiency of the diesel combustion. In more recent diesel engines, injection of fuel is done at very high pressures (of the order of hundreds of megapascals) to make the droplets of fuel fine so that they can mix quickly with the air. Historically, pressures of the order of 100 MPa have been regarded as high injection pressures but current common rail systems have a pressure of 160-180 MPa (1600-1800 bar) as a matter of routine, and even higher in production engines. High manufacturers have devised systems that are approaching the 2500-2700 bar and experimental prototypes have approached the 3000 bar (300 Mpa) threshold. These extremely high pressures favour good fuel atomization - the fuel is dispersed into very fine droplets that evaporation takes place within a short time - and reduce the ignition delay (the period between fuel injection and the start of combustion). The outcome is a more complete and quicker combustion of the fuel increasing the proportion of fuel energy emitted at the most suitable moment in time.

Empirical research has proved that increase in injection pressure enhances combustion efficiency and engine performance. To illustrate, Mohan et al. (2013) also observed that pressure in the fuel injection increases the fuel atomization rate and the combustion rate, consequently improving the brake thermal efficiency (BTE) of the engine (Mohan et al., 2013, as cited in Dahham et al., 2022). With increased pressure of injection, shorter combustion times and more of the fuel burns at high cylinder pressure (terminally closer to a theoretical constant-volume burn), and the thermodynamic efficiency of the cycle is increased. One of the studies mentioned by Dahham et al. (2022) indicated that 200 MPa rail pressure combined with other methods provided a BTE of up to about 46-50% in a single-cylinder study diesel. Delphi and Denso have also stated that they will have 2500+ bar (up to 3000 bar) common rail systems in production engines to minimize fuel consumption and emissions. In fact, increased pressure leads to the production of smaller fuel droplets, which reduces the time taken in combustion and enhances the extent to which fuel burns. The trade-off here is that both extreme injection pressures demand highly specialized materials and very precise machining to handle the pressure, and demand a lot of drive power to operate fuel pumps (common rail pumps may need kilowatts of power). However in heavy duty applications the efficiency gain exceeds these costs.

Besides increased pressure, there are various injection strategies that have increased diesel combustion efficiency. Common rail systems permit control of injection timing and quantity to be flexible, and such tactics as pilot injection, main injection and post-injections within each engine cycle are possible. To initiate a controlled combustion a small pilot injection a few crank-degrees prior to the main injection is used to decrease the ignition delay of the main fuel charge. It leads to a less turbulent process of heat release, slower rate of peak pressure increase, which not only reduces the level of combustion noise, but also allows a somewhat more advanced main injection timing, at a higher level of combustion efficiency, without generating excessive knock or pressure shock levels. Multi-stage injection is able to bring combustion nearer to the ideal (heat addition near constant-volume) by controlling the heat release curve. Earlier ignition timing and improved timing implies that a larger portion of the fuel is burned during the time that the piston is close to the top dead center, enhancing the amount of work extracted during combustion (i.e. greater effective expansion of the combustion gases). Multiple injections also provide rate shaping to prevent a significant amount of fuel burning towards the end of the expansion cycle (which would be less efficient). It has been demonstrated that the optimal utilization of pilot, main, and occasionally post-injections can increase the thermal efficiency besides decreasing soot and NOx emissions (through local equivalence ratios and temperatures) (Mohan et al., 2013). An example is that a pilot injection can be used to burn a small amount of fuel initially and raise the temperature of the in-cylinder to allow a larger main injection to be better vaporised; a small post-injection can be used to help burn-out soot in the cylinder (however, post-injections are frequently employed in emission control such as regenerating particulate filters). The current injectors have the capability of making 5-8 injection events per cycle with electronic control, compared to the one shot diesel injections. The ability of common rail injection to operate with high pressure regardless of engine speed and multiple injections is hence one of the pillars of improving combustion efficiency in diesels (Jaaskelainen and Khair, 2020).

Therefore, higher fuel injection systems enhance the effectiveness of combustion since the introduction of the fuel occurs in an optimal way: the finely atomized fuel is well mixed and has timely introduction. Increased injection pressures and repeated injection will result in further complete combustion (less unburned hydrocarbons and CO) and indicated higher efficiency and lower specific fuel consumption. These benefits are realized through the assistance of strong materials and accurate control electronic to support the extreme pressures and rapid actuator response. Consequently, the fuel injection technology has continued to be among the best mechanisms of increasing the efficiency of the diesel engines in the contemporary designs.

Air Management Techniques and Boosting

Another important tip on enhancing the combustion and efficiency of diesel engines is provision of more air (and oxygen) to the cylinder. The use of turbocharging has become almost a standard in the contemporary diesel engines as it enables more fuel to be burnt effectively by increasing the volume of air inducted each cycle (increasing the air/fuel ratio). A turbocharger utilizes waste exhaust energy to power a compressor which raises the pressure of intake air - essentially a form of energy recycling which enhances the thermodynamic efficiency of the engine by using exhaust enthalpy which is otherwise wasted. With a higher density air charge (usually 2-4 times atmospheric pressure in contemporary turbos) packed in the cylinder, the engine is able to burn more fuel in each stroke, and generate more work without raising the displacement. Notably, this also enhances the efficiency of combustion since an increase in excess-air factor will guarantee an increase in the extent of fuel oxidation (diesels are lean, and the greater the amount of air, the less the chances of localized rich regions with soot or unburned fuel). Turbocharging therefore has a direct effect on increased power density and increased efficiency; a typical turbocharged diesel consumes 30-40 per cent of the brake specific fuel consumption of a similar naturally aspirated engine at similar powers, much of this is due to more efficient combustion and greater pressure ratio which allows a more optimal cycle (Heywood, 1988).

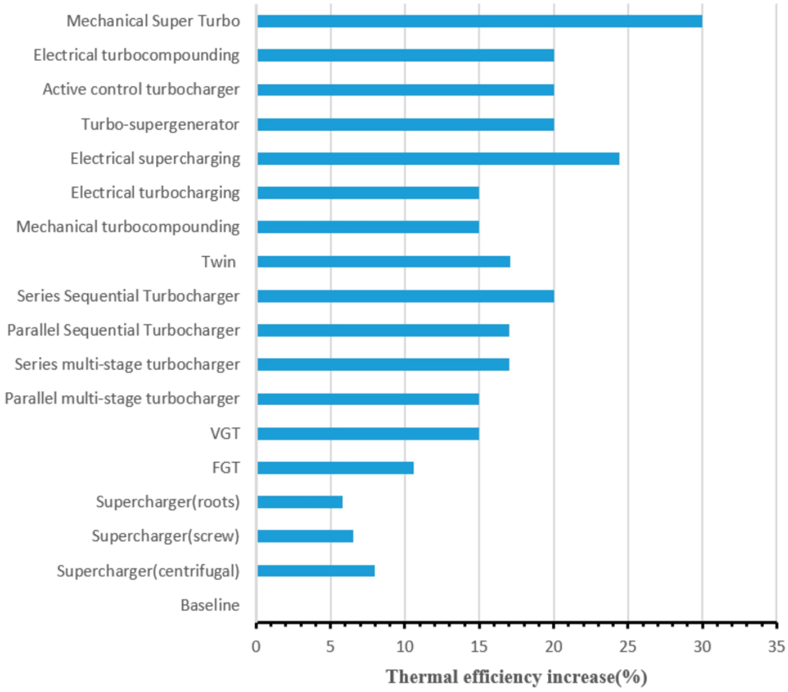


Figure 1: Influences of various boosting and air-management systems on the diesel engine efficiency (relativized increase in brake thermal efficiency relative to a naturally aspirated base). Even more complex boosting processes such as two-stage sequential turbochargers, electric-assist turbochargers, turbo-compounding have demonstrated an enormous payoff (meaning, over 10% improvement), whereas more basic

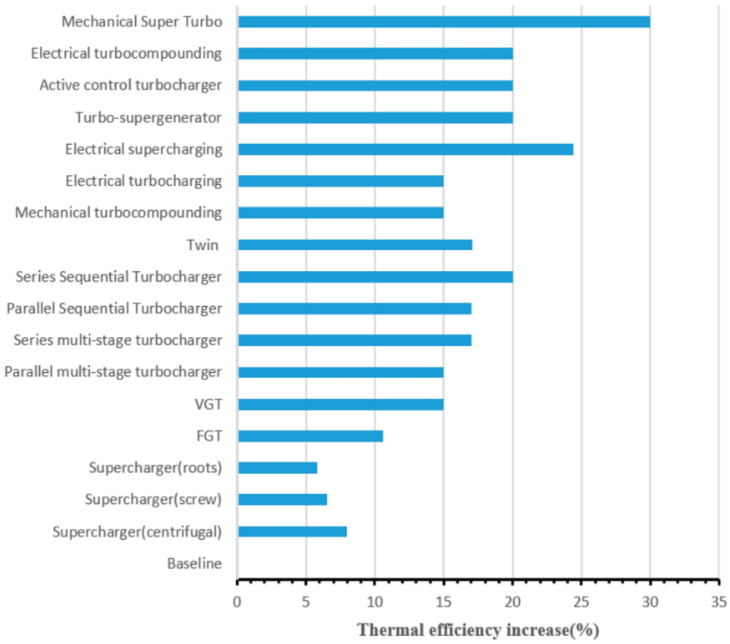
boosting processes (e.g. single mechanical superchargers) have only a smaller payoff. This indicates the higher potential of high-efficiency turbo systems to recover exhaust energy and ensure optimal air ratios of fuels with regard to operating conditions. The data is based on Dahham et al. (2022), who synthesized the findings of different strategies in boosting.

Simple turbocharging itself can increase efficiency by a significant margin, though more sophisticated methods of turbocharging are still being pursued. The Variable Geometry Turbocharger (VGT) is one of such inventions. On the turbine side of a VGT, the guide vanes or nozzle geometry can be adjusted to enable a VGT to adjust the incidence of the exhaust gas on the turbine wheel. This allows the turbo to have high efficiency and boost over the broader engine speed range. When the engine is running slowly (exhaust flow), the vanes are closed to raise the speed of the turbine and reduce the dreaded turbo lag, and to give good boost even with a low exhaust energy; when the speed is high, the vanes are opened so the backpressure is avoided and the turbo overboosts. This leads to a better supply of air under any conditions and enhances not just transient, but overall efficiency (through loss of pumping and sufficient air to burn fully even at low speeds). These improvements have demonstrated that by substituting a fixed-geometry turbo with a VGT, a thermal efficiency increase of the order of 15 per cent can be achieved. That is, improved matching of the turbocharger by variable geometry maintains the engine at a nearer to the optimum air-fuel ratio and minimizes the inefficient and under-boosted operation.

In high-output engines two-stage (or sequential or compound) turbocharging is yet another mechanical efficiency enhancement method. Two turbochargers are employed (one smaller high pressure and one larger low pressure), either in series or staged mode, in a two stage system. The smaller turbo offers fast boost at low rpm whereas the larger one kicks in at higher flow rates or they can work together to achieve very high boost pressures. This design is able to sustain high boost throughout the speed/load curve and enhance the low-end torque without affecting the top-end airflow. Based on modeling and experimental evidence summarized by Dahham et al. (2022), a two-stage turbocharger system is possible to achieve the same thermal efficiency of a diesel engine by about 17 percent compared to a single-stage system. The increased supply of air and intercooling between stages (to lower intake temperature and raise density) gives more complete combustion and a higher effective expansion ratio (cylinder pressure is higher). In research programs, two-stage boosting played a significant role in getting some engines to BTE above 50% in some engines. It can also be improved through turbocharger to allow engine downsizing, which is a strategy in which a smaller engine (with lower friction and pumping losses) is operated on high boost to satisfy power requirements. Downsized turbo-diesels spend more time at higher loads where they are more efficient, therefore enhancing real world efficiency. It has been extensively applied in passenger car diesels and has been used to achieve fuel economy.

Turbo-compounding is one more method of reclaiming exhaust energy. In turbocompounding a second turbine (referred to as a power turbine) is installed in the exhaust stream (in series or parallel with the turbine of the main turbo) to recover additional exhaust energy following the turbocharger. In mechanical turbocompounding this power turbine is gears coupled to the crankshaft, which provides additional rotational force to the engine. In electrical turbocompounding, the turbine is used to power a generator that transforms that energy into electricity (that can be utilized in a hybrid system or vehicle electrics). Some heavy-duty diesel engines (such as some Scania and Volvo truck engines) have employed mechanical turbocompounding and have been able to achieve a few percentage points of efficiency improvement. According to Jaaskelainen and Majewski (2020), turbocompounding is generally able to offer 3-5 percent of further efficiency gain in heavy-duty engines. An example would be a turbocompounded engine that would increase its BTE by 45 percent to a range of 47 percent. This is a small contribution, but it is made by merely reclaiming wastes of heat. A difficulty, however, is that Exhaust Gas Recirculation (EGR), which is widely employed in the minimization of NOx, bypasses some of the exhaust flow around the turbine and, therefore, can minimize the advantage of turbocompounding. It implies that the benefits of turbocompounding are most significant in cases when the EGR rates are low or when the working conditions can provide an abundance of excess exhaust energy. However, during steady-state high-load operation, turbocompounding is an efficient way of enhancing the amount of work that is extracted out of the cycle leading to an overall increase in efficiency.

Another method in the air management field is the use of superchargers (mechanical driven compressors). The engine crankshaft (through a belt or gears) drives a supercharger (e.g. Roots or twin-screw type) to increase intake pressure. It does not require exhaust energy to boost (even in very low-speed operation) as a turbo does, but the disadvantage is that it also requires a small amount of shaft power to operate the compressor. Previously, this loss was parasitic and diesels had fewer superchargers compared to turbos. Other modern engines employ combinations of supercharger and turbine (in some cases also called super-turbo systems) to combine the best of the - the turbo gives high-speed boosts efficiently, whereas an additional supercharger is used to assist at low rpm. One analysis (Alshammari et al., 2019) found that a mechanically driven supercharger alone could potentially only improve diesel BTE by the order of 3-7 percent (since the improvement of air combustion assists combustion, and running the blower costs power), but an integrated super-turbo (turbocharging and mechanically driven supercharger) showed that much greater improvements (several times better relative efficiency in a conceptual design) could be realized. Electric-assist turbochargers or electrically driven compressors (e-boosters) are increasingly replacing purely mechanical superchargers in diesels, since they can provide transient boost with no sustained parasitism and so enhance transient efficiency and reduce lag.



Intercooling (charge-air cooling) is typically combined with turbo/supercharging to make it even more efficient. Intercoolers enhance air density, and so decrease the amount of work needed to compress the intake air during the intake stroke (greater mass per unit volume leads to less compression work per unit volume). Intercoolers cool the compressed intake air (this is typically achieved by an air-to-air heat exchanger), which causes the work to compress the intake air to be lower than it would otherwise be. Peak combustion temperature is also decreased by cooler intake, potentially causing a decrease in NOx formation and permitting slightly earlier aggressive injection timing without knock. In general, intercooling will mean that the extra air provided by boosting is added to the combustion to the maximum benefit and none of the negative impact of high intake temperatures.

To conclude, boosting methods enhance the efficiency of diesel combustion in two main ways, by making sure that there is sufficient oxygen supply and wasting energy is recovered. Turbochargers (particularly with modern day features such as VGT and multi-stage configurations) boost considerably the volume of fuel that can be burnt cleanly and enhance the efficiency of the thermodynamic cycle by enhancing the effective compression/expansion ratio. Figure 1 (above) revealed that even simple single-stage turbocharging provides significant improvements in efficiency, and more advanced systems (two-stage, turbocompound, electrically assisted turbos) have the power to drive efficiency to even greater places. In fact, during U.S Government Department of Energy "SuperTruck" demonstrations, new turbocharging and waste heat recovery enabled engines to achieve 50-52% BTE (approximately 12-17% better than a 2010 baseline). The only warning is that increased boost and fuller combustion would push peak cylinder pressures and temperatures higher which may increase engine stress and NOx emissions - so to control these parameters, powerful engine components and post-treatment of emissions (or EGR strategies) are needed. Although these issues exist, better air-management is one of the pillars towards enhanced diesel efficiency.

In-Cylinder Air Motion And Design Of The Combustion Chamber

Even the mechanical design of the combustion chamber itself is critical regarding the efficiency of combusting fuel in a diesel engine. In contrast to spark-ignition engines, diesels inject the fuel into the hot air under high pressure and the formation of the mixture is mostly governed by the forces of turbulence and sprays of fuel. Hence, the geometry of the piston bowl, the geometry of the intake port, as well as the mechanisms to create swirl or turbulence are very important to attain a complete mixing of the fuel and the air. Increased mixing results in complete combustion (increased combustion efficiency) and increased burn rates (increasing the thermodynamic efficiency by giving up heat when the piston is close to TDC).

The majority of contemporary direct-injection diesel engines have a re-entrant bowl design piston - a bowl at the piston crown that encourages swirl and squish of air as the piston ascends. The flowing air in the bowl aids in the dissemination of the injected fuel and also mixes. It has been demonstrated that a high power organized swirl can significantly enhance the efficiency of combustion. As an example, according to Khan (2020), swirl enhances the rate of fuel evaporation and the mixing of the air and fuel, which burns more completely. Swirl is created by engine designers by the shape of the intake ports (helical or tangential ports, which provide a rotation to the incoming air) and by the shape of the piston bowl. Each engine has an optimum swirl ratio (rotational air speed/engine speed) - too slow and there is not enough mixing of the fuel, too fast and there can be undue heat loss on the walls of the cylinder or the fuel sprays will not penetrate.

An example of a mechanical technique to increase swirl is intake of guide vanes or other flow directing devices. Najafi et al. (as cited in Khan, 2020) tested a diesel generator where the guide vanes were included in the intake to enhance more intense swirl and tumble motion in the air. A 35deg vane angle was determined to be the best, which produced the highest efficiency, lower brake-specific fuel consumption (BSFC), and low emissions. By changing the vane geometry (angle, height, number), researchers would be able to enhance the airflow pattern to have the fuel in the injector broken up and dispersed more evenly in the combustion chamber. The outcome is a less turbulent combustion and reduced regions of rich mixture, therefore, a more complete burn of the fuel (better combustion efficiency) and less soot. With high-viscosity biodiesel fuels, whose atomization is less good, the addition of a swirl/tumble device in the intake reduced the combustion inefficiency of the slow mixing of the fuel. These results demonstrate that even fairly basic mechanical changes to the intake - which is, actually, bending the motion of air - can bring about objective efficiency gains.

Swirl is not the only combustion chamber geometry optimization. The piston bowl shape is frequently shaped to form squish areas (where the piston is very near the head, so that the air is squeezed off at high speed) that produce turbulence and force the air into the bowl. The current pistons have reentrant lips that assist in redirection of air upwards and allow the generation of more kinetic energy that is turbulent in the course of the combustion event. Increased turbulence accelerates the mixing and combustion processes, which helps to increase the rate of pressure increase (better resembles ideal constant-volume combustion). But the designers have to strike a balance in this - excessive turbulence may cause more losses of heat to the walls. The geometry of the bowl is also intended to maintain the flame distant to the walls (to minimize heat loss and extinguishing unburned fuel). The optimization of shapes of the combustion chambers, both computationally and experimentally, remains an active multi-objective (maximisation of the combustion efficiency and reduction of emissions) research topic.

The second mechanical method is the control of the spray targeting through the injector nozzle geometry. Although the nozzle design (number of holes, hole size, spray angle) is technically considered a component of the fuel system, the design of the nozzle (number of holes, hole size, spray angle) is designed so that the fuel plumes enter the air pockets without striking the walls. This is in a way co-design of the mechanical injector and chamber. Better spray targeting will mean that virtually all fuel will get a place to react with air. As an example, multi-hole injectors (5-8 holes) with well-informed angles will evenly disperse fuel in the bowl and avoid over-rich areas and enhance the overall combustion efficiency (Payri et al., 2016).

To conclude, in-cylinder air movement (swirl, tumble) and chamber geometry are improved to optimize combustion because it leads to rapid and complete mixing of fuel and air. Other mechanical improvements such as intake port improvements (swirl ports, guide vanes) and improved piston designs have been demonstrated to increase thermal efficiency by several percent and also lower emissions. Such increases in combustion efficiency are very useful at light loads or with challenging fuels (as with high-cetane biofuels) when mixing is the bottleneck. Their primary concern is that any aerodynamic gain has to be offset by some possible limitations such as augmented surface area (which may raise heat losses) or the intricacy in production. However, the swirl/turbulence traits are nowadays universally introduced into modern diesels as an essential element of high-efficiency combustion.

Variable Valve Timing and Miller Cycle

The valve timing strategies which are a traditional concept of gasoline engines have also turned out to be useful in diesel engines in enhancing efficiency. The diesel engines can put in place strategies like the Miller cycle or internal exhaust gas recirculation (which affect the effective compression and expansion process) by enabling the use of Variable Valve Actuation (VVA) systems - which can adjust the timing or duration of the valve opening. The Miller cycle is where the intake valve is closed at a reduced (or increased) effective compression stroke but with a normal or extended expansion stroke. The concept here is to get a larger expansion ratio than the compression ratio thereby extracting more work out of the combustion products (improvement in the thermodynamic efficiency). Basically, the Miller cycle is an approximation method of an Atkinson cycle, or a method of reducing the effective compression temperature (to prevent knock or to permit more efficient high-pressure combustion).

Miller cycle implementation in diesel engines typically needs sophisticated boosting to offset the smaller effective compression (some of the air is forced back out or not intake-valve is not intake-valve captured). Miller timing when performed correctly can lower the peak combustion temperatures and pressures (to the benefit of emissions) and a little raise efficiency. Guan et al. (2021) discovered that aggressive Miller cycle coupled with high boost and EGR enhanced fuel conversion efficiency by approximately 1.5% at high load (1.7 MPa IMEP), and decreased total fuel consumption by approximately 5.4 per cent. The same study also observed that Miller timing produced a negative effect at low engine speeds (modest efficiency loss) but gave benefits at higher speeds where the turbocharger was able to fully offset the lower intake charge. This means that Miller cycling is optimum when turbo efficiency is high, as well as the engine is not air limited.

VVA modern engines are able to change the timing of intake valve closing on command. A typical example is an early Miller cycle (when the intake valve closes early in the compression cycle) which in effect decreases the compression ratio visible to the air, thereby decreasing compression work and temperature. The expansion stroke, though, continues to make use of the entire geometric compression ratio of the engine, thus, the expansion ratio is greater than the compression ratio - resulting in a more efficient transformation of heat to work. A disadvantage of Miller cycle is, it may increase the ignition delay or decelerate the combustion kinetics (in a diesel, at too high a rate, it can increase the difficulty of auto-igniting the fuel). Hence, it usually has to be combined with other methods such as a higher boost or greater injection timing to prevent the worsening of combustion.

The other advantage with VVA is that internal EGR is controllable (through lengthening of valves to allow residual gas to flow) or that strong swirl can be produced at some operating conditions (some advanced systems are capable of varying the lift of swirl control valves). Part load pumping losses can also be reduced by full flexible valve control (although diesels already have no throttle, part load pumping losses are primarily caused by turbo and EGR restrictions). The article by Flierl et al. (2013) showed a fully variable valve lift and timing system, which increased the fuel economy of a diesel engine by as much as 13 percent under some conditions. This enhancement was a result of mixes of Miller-type functioning and loss of gaseous exchange. In another study mentioned by Dahham et al. (2022) it was discovered that the use of continuously variable valve lift (on the intake) had the potential to cut BSFC by over 20 percent at 2000 rpm in a gasoline engine environment, which highlights how important valve strategies can be - the impacts would be somewhat different but still significant in diesels.

In practice, Miller valve timing is combined with very high pressure turbocharging with a number of modern large diesel engines (e.g. marine or stationary engines) to increase efficiency and reduce NOx. In the case of automotive diesels, other engines use cam profiles which effectively provide a mild Miller cycle to trade off NOx and efficiency (Miller decreases NOx by decreasing the combustion temperature). The major weakness is that a Miller cycle diesel must have a very efficient turbocharger - failure to which the power and efficiency will be lost due to the smaller intake fill. As one of the studies indicated, the Miller cycle process requires very high efficiency of turbochargers in an effort to reduce the consumption of fuel. This has been easier with the modern turbo designs and even electrical aids to the turbochargers.

To conclude, variable valve timing (with or without Miller cycling) is an engine technology that can slightly modify the diesel combustion cycle to realize increased efficiency. This is done by decreasing the effective compression (and therefore compression work) and keeping the expansion constant, so that the ratio of expansion to compression work is made more favorable, and thermal efficiency is increased. Its trade-offs are high boosting dependence and possible problems in combustion timing but research and some actual production demonstrations have indicated that a few percent of efficiency increase, particularly at high loads, is obtainable. VVA is also being studied at the PhD research level to allow more advanced modes of combustion (such as control of exhaust temperature to allow HCCI modes, see below). In general, Miller timing through VVA is a complementary method, which when used in conjunction with other methods, causes diesel efficiency to shift upwards.

Thermal Barrier Coatings and Low Heat Rejection Engines

An engine spends a significant amount of fuel energy as heat radiated into the cylinder walls, cylinder head, and piston. The amount of this heat that could be trapped in the gases would be utilized in expansion and more work could be produced thereby increasing efficiency. This is the principle in Low Heat Rejection (LHR) engines, in which the insulation (or Thermal Barrier Coatings (TBCs)) cover the combustion chamber surfaces to minimize heat loss. In a modern diesel, heat may be lost in form of coolant and oil to the tune of 20-30% of fuel power. LHR methods seek to reduce this percentage thus raising the proportion of energy that does useful work.

Mechanical implementation, which is also known as ceramic coating, entails coating the piston crown, cylinder head and occasionally the valve faces with low-thermal conductivity and high-temperature, low-thermal ceramic (such as zirconia-based ceramics). As an example, a two-layer coating on piston and valves has been experimented with; a bonding layer of NiCrAl and a top coating of Yttria-stabilized Zirconia (YSZ) some 400 mm thick. These ceramics will be able to significantly decrease the amount of heat transfer through the metal structure. In the reviewed studies, Khan (2020) found that diesel engines with ceramic-coated combustion chambers performed better. In another experiment a single-cylinder DI diesel with piston and valve coating, using biodiesel, exhibited better brake thermal efficiency and much lower BSFC than the uncoated engine. The increase in efficiency was explained by the fact that during combustion less heat was lost - more of the heat remained in the gas to propel the piston. A different study established that under TBCs and an optimized fuel (biodiesel blend with additive), the coated engine was more efficient and the CO and HC emissions were even a bit lower than the baseline, but the NOx emissions were inclined to be higher. The rise in NOx is anticipated to occur due to the fact that the higher the combustion temperature (through retention of heat) the higher the formation of NOx (thermal NOx mechanism increases with temperature). In fact, in a large number of LHR experiments, there is a trade-off in that efficiency may be increased by a few percentage points, whereas with no other precautions, the increase in NOx may be enormous.

The extent to which LHR designs can be effective is usually a few percent, though situational. The reduction of heat loss is highly advantageous at great loads, but at low loads the advantage might be less, or even negative, depending on whether the coating raises the exhaust losses (some coating may raise the exhaust temperature as more heat is retained in the gas that is not completely expanded). Initial projects by Cummins in the 1980s to make an engine that ran on ceramic pistons, liners, and heads (so-called adiabatic diesel engines) had shown that over 50% thermal efficiency could be achieved with a turbo-compounded LHR engine - a very high figure in those days. Nonetheless, there were problems with durability (thermal cracking of coating, piston strength), and NOx emissions. The modern TBC materials and application techniques (plasma spraying, etc.) have become better and the idea has become somewhat more feasible. Certain production engines are selectively coated (such as on piston crowns, mostly due to durability reasons, though with some benefit of retaining some heat).

Finally, thermal barrier coating and low heat rejection ideas are mechanical modification of the heat transfer properties of the engine to enhance combustion efficiency. They do this by maintaining the combustion chamber at a higher temperature so as to hasten the evaporation and ignition of fuel and to guarantee a more thorough combustion of heavy fuels (which can also decrease unburned HC and soot). They obviously maximize heat losses, thus increasing a proportion of energy that is converted to work. The drawback is an increase in the temperature of the components, which may impact the life cycle, degradation of oil, and NOx emissions - i.e. LHR technologies usually require additional cooling of some components (stems of the valves, etc.) and a powerful emission control system. On a research level, LHR engines still hold a potential to propel diesel efficiency to new heights, and even minor use of TBCs is already doing that in some of the newer designs.

Advanced Combustion Modes (HCCI, PCCI, RCCI)

In addition to the conventional diesel combustion (diffusion combustion with direct injection), scientists have been studying new high-technology combustion regimes which radically change the way fuel and air interact, in the hope of making them more efficient and less emitting at the same time. Although such strategies frequently need special control of fuel injection or fuel properties (not strictly mechanical changes), they are listed because they are future-oriented methods which can significantly increase the efficiency of the combustion. It is worth noting that there are two such concepts, namely Homogeneous Charge Compression Ignition (HCCI) and Reactivity-Controlled Compression Ignition (RCCI), which have demonstrated highly high efficiency in laboratory experiments.

In HCCI, the fuel and air mixture is forced into the cylinder, and it lightens on its own all over the cylinder, not through a spreading flame caused by a single injection point. Since the mixture is lean and already mixed, the combustion takes place in numerous locations at once, which makes the burn very fast and comparatively low temperature. HCCI with diesel may be through early injection or just fumigating a fuel into the intake air. The benefit is a combustion that is nearer to constant-volume and less heat losses (the combustion is fast and at lower peak temperature), and has higher thermal efficiency. According to Sadeq et al. (2025), experimental HCCI engines have already reached thermal efficiencies of 50, as good as the best diesel engines, but with significantly lower NOx and particulate emissions. The ignition timing in HCCI is hard to control, however, (it is auto-ignition of a homogeneous mixture) and the operating range is small (it can knock at high load and misfire at low load). HCCI is therefore not a diesel production solution yet, however, it shows that new combustion regimes have the potential to increase efficiency by altering the mechanics of combustion itself.

RCCI is a similar principle, which employs two fuels of varying reactivities to vary the combustion phasing. A high-octane (low cetane) fuel such as gasoline or ethanol is usually mixed (port-injected) in advance to create a lean background charge, and a small direct injection of diesel (high cetane fuel) is initiated to cause combustion. The outcome is a partially premixed combustion that is more controlled than the HCCI yet much more homogenous than the traditional diesel combustion. RCCI has demonstrated extremely high efficiencies in research engines - in some studies, fuel consumption reduction by up to 43 percent in BTE has been reported. In addition, due to low-temperature low-lean combustion, RCCI is able to decrease NOx by more than 90 percent. In a single experiment, RCCI recorded gross indicated thermal efficiencies of approximately 56 percent in a heavy-duty engine at a medium load. This would represent, after mechanical losses, maybe - 50-52% of BTE - still an impressive increase over conventional combustion. This is because the efficiency gains in RCCI are due to the combustion occurring in a more ideal way (a higher proportion of the heat release happens at high pressure and the loss of heat is less because the combustion temperature profiles are more gradual and the combustion duration is less).

RCCI or HCCI in a production engine would need mechanical flexibility: a more sophisticated fuel injection system (in the case of dual-fuel), possibly different piston designs (to fit new combustion modes) and a compression ratio that is typically optimized. These modes overlap a purely mechanical technique with a fuel/control technique. Nonetheless, they highlight that novel methods can dramatically enhance combustion efficiency - using RCCI, it is possible to raise the fraction of fuel energy converted to work by decreasing the amount of heat transfer lost and by decreasing the amount of combustion timing lost (it extends the effective constant-volume phase of combustion and eliminates late-burning fuel). The difficulties are in the control of combustion in a wide range of speeds and loads and the inability to cope with such problems as the high rate of the pressure rise or incomplete combustion at extremes.

There are also partially Premixed Compression Ignition (PPCI) or other hybrid modes, in which injection timing is sufficiently early to permit some premixing, but sufficiently late to prevent full homogeneous autoignition. Another general goal of these strategies is the more efficient combustion process. Most of these sophisticated modes are based on several injections, high EGR rates and in some cases special piston designs to form the combustion. Mechanically, an engine may require greater compression ratio or very high flexibility of the fuel injection to allow HCCI/RCCI to be successfully run at some points.

The implication of this review in the future is that diesel engines may have mechanisms that allow them to switch to these combustion states in sections of the operating map, and therefore attain greater efficiency when suitable. An example is that a diesel engine can use conventional combustion at full load (to be stable) and RCCI at cruise load to be efficient. Mechanically, enabling technologies to this are having two-fuel injection (diesel and gasoline ports) and possibly variable valve timing (to manage residuals or effective compression). Although HCCI/RCCI are not currently popular in the production process, they have been shown to potentially dramatically increase combustion efficiency - one experiment showed a maximum efficiency of up to 60% with optimized RCCI conditions, potentially equivalent to an effective BTE of approximately 55%. To make this efficiency practical, a combination of all the methods mentioned might be needed: high-pressure injectors, advanced boosting, electronic controls that are more precise, and perhaps new engine architectures.

Conclusion

The diesel engines of the modern world have seen unprecedented advancements in the efficiency of combustion due to numerous mechanical improvement methods. Innovations in fuel injection - in particular, the high pressure common rail types, and multiple injection schemes - assure a finely atomized fuel and the most opportune timing that results in increased comprehensive and quicker combustion. Enhancements in increasing engines such as turbochargers (including VGT, two-stage turbocharging, and turbocompounding) add more air into the cylinder and reuse the exhaust energy, significantly increasing the thermodynamic efficiency of the engine, and allowing it to be downsized without any loss in performance. At the same time, the combustion chamber and intake airflow should be designed carefully (piston bowl geometry, swirl induction devices) to ensure that fuel and air are thoroughly mixed, which is important to burn all the fuel and produce a low level of emissions. The Miller cycle through variable valve timing is just one way of showing how the mechanical control of the valve events can be further used to adjust the combustion cycle to gain efficiency, although again, synergy with turbocharging is required. Also, low-heat-rejection designs with thermal barrier surfaces demonstrate that even the thermal characteristics of engine material can be designed to minimize energy loss and increase efficiency - at the expense of controlling the temperature of higher parts and NOx emissions.

It is necessary to mention that most of these mechanical methods influence each other. The use of Miller cycle valve timing by an engine would rely on a high-efficiency turbocharger to sustain air flow, and the advantage of a turbocompounded engine would be compromised by EGR flow to emissions. Thus, a holistic process of improvements that consider various factors of the efficiency equation (speed of combustion, completeness, gas exchange losses, heat losses, and so on) is the most effective. This is demonstrated by such programs as the SuperTruck developed by the US DOE where the inclusion of an advanced fuel injection, two-stage intercooled turbocharging, turbocompounding, friction reduction and other additions have produced heavy-duty diesel engines with approximately 50 percent BTE - about 15 percent higher than the state of the art before it. In the future, it seems that a target of 55 percent or more BTE of diesel engines is within reach, and further development of these technologies may result in new modes of combustion (The SuperTruck II of DOE aims to reach 55 percent BTE).

In a PhD level scenario, future research is probably to be on refinement of these mechanical methods and elimination of their shortcomings: such as the development of resilient material to be injected into 3000 bar systems, the creation of adaptive turbocharging systems (including electrically assisted turbo) to perfectly match the engine air requirements, or introduction of variable compression ratio systems to dynamically optimize the cycle efficiency. Simultaneously, the issue of emission control is a parallel one - in many cases, the methods that promote efficiency in combustion (greater pressure, temperature) raise NOx or noise, which is why such approaches as high-efficiency EGR cooling, advanced aftertreatment, or even a hybrid engine are under consideration to make sure that efficiency gains are not achieved at the cost of environmental performance.

Finally, contemporary diesel engines are very efficient due to a combination of mechanical inventions that increase combustion. Increasing the ideal way of injecting fuel, delivering plenty of air and ideal cylinder conditions, minimizing the losses of heat and friction and intelligently controlling the combustion event, engineers have gradually narrowed the discrepancy between real engines and theoretical efficiency limits. As further work is done (including working with more advanced regimes of combustion), diesel engines may possibly reach and even exceed 55 percent brake thermal efficiency in the future, establishing them as a highly efficient power source. These new peaks of efficiency in combustion will be focused on by the techniques discussed in this paper - between high-pressure injection and turbo-compounding.

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