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Review Article

COMPREHENSIVE REVIEW OF INNOVATION IN PISTON ENGINE AND LOW TEMPERATURE COMBUSTION TECHNOLOGIES

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Highlights:

- mechanical efficiency can be increased through novel valve train designs utilising variable valve action or camless valve drives;
- variable compression ratio can improve mechanical and combustion efficiency;
- low temperature combustion strategies can improve combustion efficiency and lower emissions;
- modification to the traditional piston engine layout, like the 5-stroke, opposed piston and membrane engine can yield greater efficiency.

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Abstract. Global transport today is mainly powered by the Internal Combustion Engine (ICE) and throughout its century and a half of development it has become considerably more efficient and cleaner. Future prospects of the ICE rely on the scientific work conducted today to keep this trend of higher efficiency and cleaner emissions in new engines going. The aim of this article is to give a comprehensive review of development directions in novel piston engine designs, which seek to overcome the drawbacks of the ubiquitous 4-stroke piston engine. One of the directions of development is devoted to improving the mechanisms and the general layout of the piston engine to reduce losses within the engine. Research teams working with alternative engine work cycles like the 5- and 6-stroke engine and technologies for extracting waste heat seek to reduce thermal losses while novel layouts of valve trains and crank assemblies claim to significantly improve the mechanical and Volumetric Efficiency (VE) of piston engines. These novel ideas include camless or Variable Valve Action (VVA) and engines with Variable Compression Ratio (VCR) or opposed pistons. One alternative approach could also be to totally redesign the reciprocating mechanism by replacing the piston with some other device or mechanism. Additional scientific work is investigating Low Temperature Combustion (LTC) technologies such as Turbulent Jet Ignition (TJI) and Homogeneous Charge Compression Ignition (HCCI) and its derivatives like Premixed Charge Compression Ignition (PCCI) and Reactivity Controlled Compression Ignition (RCCI) that have shown improvements in thermal and fuel conversion efficiency while also significantly reducing harmful emissions. These combustion strategies also open the path to alternative fuels. The contemporary work in the combustion engine fields of research entail technical solutions from the past that have received a modern approach or are a completely novel idea. Nonetheless, all research teams work with the common goal to make the piston engine a highly efficient and environmentally friendly device that will continue to power our transport and industry for years to come. For this, solutions must be found to overcome the mechanical limitations of the traditional layout of the piston engine. Similarly various improvements in combustion technology are needed that implement state of the art technology to improve combustion characteristics and reduce harmful emissions.

Keywords: piston engine, membrane engine, 5-stroke engine, 6-stroke engine, variable valve action, variable compression ratio, low temperature combustion.

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Notations

A/R – area over radius;
AFR – air to fuel ratio;
BDC – bottom dead centre;
BEV – battery electric vehicle;
BTE – brake thermal efficiency;
CAD – crank angle degrees;
CFD – computational fluid dynamics;
CI – compression ignition;
CN – cetane number;
CO – carbon monoxide;
CO_2 – carbon dioxide;
CR – compression ratio;
DI – direct injection;
EGR – exhaust gas recirculation;
EV – electric vehicle;

FPE – free piston engine;
GDCI – gasoline DI CI;
HC – hydrocarbon;
HCCI – homogeneous charge CI;
HEV – hybrid electric vehicle;
HPSV – high pressure rotary spool valve;
HRR – heat release rate;
ICE – internal combustion engine;
ITE – indicated thermal efficiency;
LEM – linear electric machine;
LPSV – low pressure rotary spool valve;
LTC – low temperature combustion;
NA – naturally aspirated;
NO_x – nitrous oxide;
ON – octane number;
OPE – opposed piston engine;
PCCI – premixed charge CI;
PFI – port fuel injection;
PM – particle matter;
PPC – partially premixed combustion;
R&D – research and development;
RCCI – reactivity controlled CI;
RE – range extender;
REEV – RE EV;
SI – spark ignition;
TDC – top dead centre;
TE – thermal efficiency;
TEG – thermoelectric generator;
TJI – turbulent jet ignition;
VCR – variable CR;
VE – volumetric efficiency;
VVA – variable valve action;
WHR – waste heat recovery.

1. Introduction

Currently 99% of worldwide transport is powered by some sort of ICE, which mainly use fuels derived from crude oil (Leach *et al.* 2020). Burning these fuels produce greenhouse gases that contributes to global warming. To limit global greenhouse gas emissions, several strategies have been developed to reduce the harmful emissions of ICE. These include increased engine efficiency, exhaust gas after treatment, alternative fuels, and as a last resort some countries have come forward with claims to ban the production of new ICE for passenger cars in the coming decades (Alagumalai 2014; Burch, Gilchrist 2020; Santos *et al.* 2021; Johnson, Joshi 2018; Leach *et al.* 2020). As an alternative, electric drivetrains have also been introduced to the market as a viable replacement for passenger cars fitted with ICE (Mali *et al.* 2022; Morfeldt *et al.* 2021; Pillai *et al.* 2022; Senecal, Leach 2019). However, heavy-duty ICE used in transport and various industries cannot currently be replaced with a fully electric alternative. This is mainly due to the batteries, which need to be large in dimensions and high in mass to cope with the high energy demand of these machines (Kalghatgi 2018; Lajunen *et al.* 2016). Therefore, for trucks, ships, planes, and other heavy-duty machinery the ICE is currently the only feasible solution (Morfeldt *et al.* 2021). In addition, small devices like portable power tools and generator sets currently use a piston engine as a power source. This means that, despite the possible ban of ICE in passenger cars, there are still areas where the development of piston engine technologies is relevant (Agarwal *et al.* 2017; Reitz 2013). Besides the historically dominant piston engine, alternative technologies for motored propulsion have been considered but none have become commercially available or have quickly faded away due to reliability issues or high emissions.

While previous reviews have focused primarily on specific technological fields in isolation, the objective of this article is to provide a comprehensive overview of these emerging technologies in parallel. In this article, some promising concepts are discussed that aim to increase the efficiency and future usability of piston engines under stricter regulations. These concepts can be broadly categorized into 2 topics – redesigning the engine layout and developing combustion strategies. Some researchers investigate novel approaches to redesign the reciprocating assembly and valve train of the prevalent 4-stroke piston engine to increase efficiency and reduce losses. Others are developing various LTC strategies to reduce emissions and increase combustion efficiency.

2. Over-expanded engines

Throughout history various approaches to improve the Otto cycle have appeared (Noga, 2018). Even today the Atkinson and Miller cycles have their place in propulsion systems with the goal to achieve higher efficiency by means of changing the ratio of the expansion and compression stroke of the standard Otto cycle (Kéromnès *et al.* 2014; Li *et al.* 2016). Driven by this notion various over-expanded engines are once again under development (Arabaci *et al.* 2015; Li *et al.* 2015; Noga, Sendyka 2014; Palanivendhan *et al.* 2016). These 5- or 6-stroke engines feature extra strokes within the engine cycle to reduce losses in the engine by utilising waste heat but are by no means a novel idea having been development since the birth of the 1st ICE (Noga 2018). These historic attempts were sadly constrained by the limitations of the technology at the time, but today's scientist have new materials and resources at their disposal that enable a new attempt at developing a functional over-expanded engine.

2.1. 5-stroke engine

A modernised 5-stroke engine was patented by Schmitz and has been simulated but also built and tested by multiple research teams (Noga 2018). In the 5-stroke engine of Schmitz (2003) the additional expansion of gases is achieved through directing the exhaust gases of a fired cylinder to a separate cylinder. In this low-pressure cylinder the hot and high-pressure gases are expanded during an additional stroke, the 5-stroke. During this stroke additional energy from the exhaust gases is extracted and utilised as usable work, instead of venting them directly to the atmosphere. A significant drop in temperature and pressure is observed after the 5-stroke but still enough energy remains that it can be once more utilised by an exhaust gas turbocharger. In some cases, so much energy is extracted, that the final gas pressure in similar or even lower than the ambient pressure (Noga 2017). In a conventional 4-stroke engine the energy stored in exhaust gases as heat and pressure is generally lost as they are vented out of the engine during the exhaust stroke. Some energy recovery is achieved through utilisation of a turbocharger, but this only contributes to a small percentage of energy still unrecovered as heat and pressure. Testing has shown that additional energy in the form of up to 18% indicated engine power was recovered with the help of additional expansion cylinders (Kéromnès *et al.* 2014; Noga 2017).

A team of researchers at Cracow University of Technology (Poland) conducted comparative tests on a 4-cylinder Otto cycle engine and a modified 5-stroke engine based on the same 4-stroke engine (Noga, Sendyka 2013). This was achieved by converting the 2 middle cylinders of the inline 4 engine to expanders for the exhaust gases of the 2 outer cylinders as seen on Figure 1.

As only the cylinder head was modified, all other assembles would still display similar characteristics of efficiency, friction, and losses. Thus, an adequate comparison of the 2 engines was possible.

Figure 2 shows the results of one of these tests. The total efficiency of the 2 engines is displayed at variable loading while the engine was kept at a constant engine speed of 2400 rpm and a stoichiometric mixture. As the displacement of firing cylinders in the engine was virtually halved, the test data was compared based on 1 dm^3 of engine displacement (Noga, Sendyka 2014). These results demonstrate that at similar loading conditions the 5-stroke engine has higher total efficiency. Similarly, the 5-stroke engine exhibited higher specific torque and power values at given engine speeds during wide open throttle conditions (Noga, Sendyka 2013).

Due to the superior heat extraction a lower than ambient pressure within the exhaust manifold can occur. This means at lower loads the engine can have a lower efficiency than a conventional 4-stroke engine. During some tests pressure in the exhaust side of the engine reached such low values that energy was drawn from the engine and in some cases even engine oil leaked into the manifold due to the negative pressure (Noga 2017). To alleviate the effects of this phenomenon the design of Lu & Pei (2015) could be implemented. They developed a split cycle engine concept based on the design of Schmitz (Lu, Pei 2015). Their idea of injecting water into the expander cylinder could increase the expansion of gasses due to water steam and reduce the occurrence of negative pressures in the exhaust manifold (Lu, Pei 2015; Wu *et al.* 2021).

In the future development work must also be done to reduce heat losses in the ducting between the fired high-pressure and expander low-pressure cylinders (Noga 2017). With shorter and wider channels that are insulated

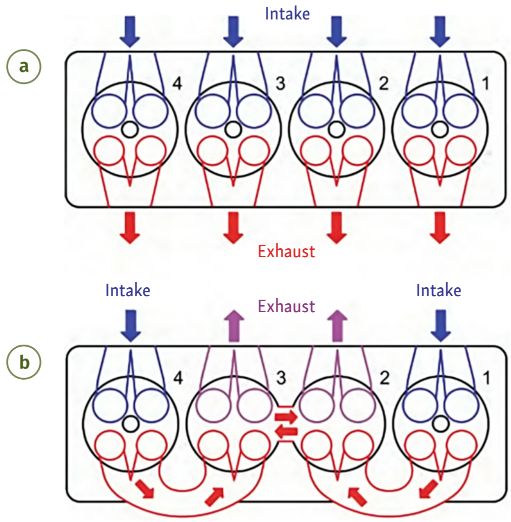

Figure 1. Sectional view of cylinder head modifications by Noga (Noga, Sendyka 2013) to convert a 4-stroke engine to 5-stroke engine

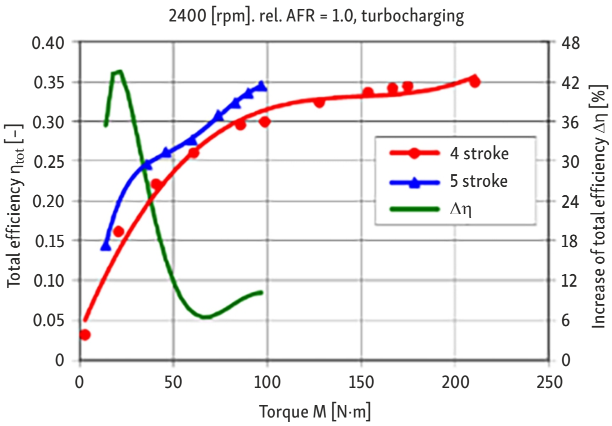

Figure 2. Comparison of total efficiencies of the 4- and 5-stroke engine, where the green line indicates the relative increase in efficiency of the 5-stroke engine (Noga, Sendyka 2014)

and properly sized valves, more energy can be transferred between the cylinders. By getting gasses with higher temperature and pressure into the low-pressure cylinder more usable work can be extracted from the gasses. This may also aid in keeping the post turbocharger exhaust gases hotter to light a catalytic converter and help reduce emissions.

The 5-stroke engine is most efficient only at fixed points of operation (Kéromnès *et al.* 2014). Luckily, this isn't an issue since hybridisation of powertrains is becoming more relevant. Utilizing this engine as a RE in a hybrid vehicle could provide the necessary niche needed for the application of this engine. As was the intent of Kéromnès *et al.* (2014) in their research. In some iterations the engine was even found to be smaller and lighter that a similar 4-stroke engine, giving it another advantage as a RE (Noga 2018; Palanivendhan *et al.* 2016).

2.2. 6-stroke engines

Another alternative to conventional engines is the 6-stroke engine, a technology that stems from the very beginning of the ICE but was not widely used for most of the ICE history (Naresh, Babu 2015). The engine is similar to a 4-stroke engine but after the exhaust stroke, 2 extra strokes of intake and exhaust occur (Figure 3). In addition to the 2 extra strokes, many other solutions like forced induction and water injection may be applied, with the goal to increase the volumetric and TE of the engine by recovering more heat energy from the exhaust gases and gaining additional power (Naresh, Babu 2015; Arabaci 2021; Chen *et al.* 2015). The engine with increase in efficiency could be suitable for future hybrid powertrains (Arabaci 2021).

The simplest designs add no complexity to a conventional 4-stroke engine, other than a modified camshaft to enable the gas exchange for all 6 strokes (Naresh, Babu 2015). However, this also means that during the 2 extra strokes no additional power is generated. The additional strokes offer better scavenging of combustion products and aid in the cooling of the combustion chamber providing for better volumetric and TE (Arabaci 2021). To recover more energy from the exhaust gases, various solutions are in development, such as various methods for water injection. The patented design from Conklin & Szybist (2010) harnesses exhaust gas energy by recompressing the exhaust gasses after a partial exhaust stroke and injecting heated water into the cylinder. The expansion of steam creates pressure and drives the piston down. Prior to injection water is heated to approximately 100 °C through a heat exchanger that is coupled with the cooling system. A similar setup is used by other water injection applications as well and enables for heat recovery not only from the exhaust gas, but also from the cooling system. Various authors have remarked upon the significantly decreases in needed cooling capacity for water injection 6-stroke engines when compared to similar 4-stroke engines (Naresh, Babu 2015; Arabaci *et al.* 2015; Conklin, Szybist 2010). WHR from the exhaust gasses could aid in increasing the water temperature over 100 °C, but requires additional complex heating systems (Conklin, Szybist 2010; Wu *et al.* 2021). The 6-stroke concept has been tested on CI and SI engines showing great promise of applicability for both engine types (Arabaci *et al.* 2015; Conklin, Szybist 2010).

Proper injection timing and system configurations could improve CI engine applications as higher backpressure demands for higher water/steam pressures and thus more energy is lost to drive the pump. Extensive research must be further conducted to simulate real world conditions and find out the actual commercial viability of this technology. Problems like short driving cycles and cold temperatures could have a drastic effect on the water injection systems leading to frozen waterlines and damage to the engine. Furthermore, water caused corrosion of internal engine parts and wear from water getting into the lubrication system are an issue. Test cycles with water of varying purity must be conducted to determine the build-up of impurities like boiler scale from the water onto the injection system and engine components. Correct quantifying of water is important not only to avoid engine damage but injecting the right amount of water into the cylinder is crucial. Too little of water has hardly any effect on the whole process and too much water can inhibit complete combustion and thus increase emissions like CO and HCs (Arabaci *et al.* 2015). Just the right amount lowers combustion temperatures to supress the formation of NO_x emissions and increases TE through WHR (Chen *et al.* 2015; Wu *et al.* 2021). To further increase the efficiency, a turbocharger could be fitted to the 6-stroke engine that extracts additional energy from the exhaust gasses during the initial partial exhaust or the exhaust stroke after recompression.

3. WHR

3.1. Water injection

Heat from exhaust gases can be extracted not only by means of applying additional expansion stroke to the 4-stroke cycle, but also by using various WHR technologies (D'Amico *et al.* 2018; Dong *et al.* 2015; Karvonen *et al.*

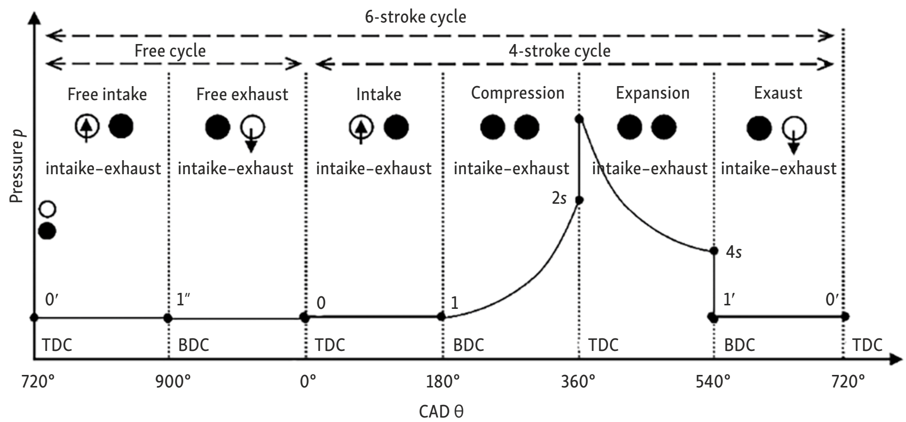

Figure 3. Pressure vs. crank angle diagram of a 6-stroke engine (Arabaci 2021)

2016; Sprouse, Depcik 2013; Uusitalo *et al.* 2014; Wu *et al.* 2021). There are many approaches to extracting heat energy from the exhaust gases and utilising it to generate additional power and some of them rely on adding extra strokes to the traditional 4-stroke engine (Chen *et al.* 2015). The abovementioned 6-stroke engine has historically been improved by using water or water steam as a working fluid to extract heat left over after the combustion process (Naresh, Babu 2015). Even today a number of research teams are investigating the possibilities of 6-stroke engines with water injection (Arabaci *et al.* 2015; Wu *et al.* 2021). By using water as a working fluid, the efficiency of the 6-stroke engine is further improved since the 5-stroke can produce additional pressure and thus engine power and does not draw energy from the engine.

Current testing has shown a 10% increase in brake power owing to decreased exhaust gas and engine wall temperatures that allow for better VE (Arabaci *et al.* 2015). The hurdles to overcome are the corrosive effect of injecting water (steam) into the cylinder, as it comes to contact with bare metal parts within the engine and also the problem of water fouling lubricating oils in the engine and increasing wearing of parts (Wu *et al.* 2021). As with direct fuel injection the pressure must be high enough to overcome the pressure within the cylinder. For diesel applications this can mean that the pressure for the water or steam must reach well beyond 15 bar, which would suffice for SI engines (Chen *et al.* 2015).

3.2. Power generation through the Rankine cycle

In addition to introducing water into the cylinder, there are other methods of WHR. One approach is to add a heat exchanger to the exhaust piping (Figure 4) to heat up a working fluid and extract the energy through a Rankine cycle to produce electricity (D'Amico *et al.* 2018; Dong *et al.* 2015; Karvonen *et al.* 2016; Sprouse, Depcik 2013; Uusitalo *et al.* 2014; Wu *et al.* 2021).

The working fluid can be water, but organic working mediums are favoured due to their ability to extract more energy from the exhaust gases (Colonna *et al.* 2015; Sprouse, Depcik 2013). As the process takes time to recover heat energy and convert it to electricity, automotive applications can be limited, but testing on large stationary industrial ICE have shown a 10% increase in power output (Bombarda *et al.* 2010; Uusitalo *et al.* 2014; Vaja, Gambarotta 2010). Current state of the art technologies could be applied to long-haul trucks as they spend many hours driving at relatively constant loads, giving time for the Rankine cycle to go through sufficient cycles to generate a considerable amount of electricity (Colonna *et al.* 2015; Sprouse, Depcik 2013). For mobile units the sizing and packaging of the system is also problematic, because of this applications on passenger cars are currently not feasible (Karvonen *et al.* 2016).

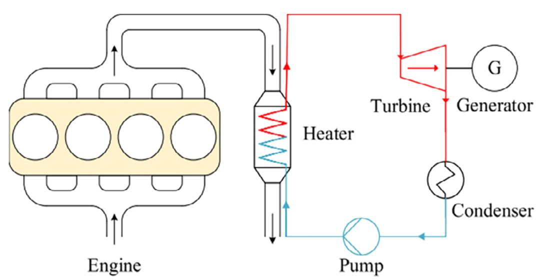

Figure 4. Simplified diagram of an evaporator and expander added to the exhaust of an engine (Wu *et al.* 2021)

3.3. Thermoelectric generation

Thermoelectric generation systems are also in development that can extract waste heat from engine exhaust gases, lubricating oil or coolant. This technology predominantly employs the Seebeck, Peltier or Thompson effect to convert heat energy into electric energy by applying a temperature gradient to a TEG module. The TEG module is sandwiched between 2 heat exchangers. The hot side is to extract heat from the engine, be it from the exhaust gases, cooling liquid or engine oil, and a cooling element on the other side to extract heat from the cold side of the TEG module and create the desired temperature gradient (Figure 5). A TEG is a solid state device, meaning it doesn't have any moving parts, thus it does not produce any noise or vibrations while operating (Burnete *et al.* 2022; Konstantinou *et al.* 2022; Ochieng *et al.* 2022; Ragupathi, Barik 2023).

The cold side can be cooled by the surrounding in addition fans or the airflow around a moving vehicle can be used to increase the cooling effect. Experiments have shown that liquid cooled solutions yield the highest efficiency. (Ochieng *et al.* 2022) As the hot side is generally permanently fixed to a heat source the heat extracting performance from the cold side has shown to influence TEG efficiency the most. Generally, TEG module efficiency is at 5 to 10%, which can be considered low (Ochieng *et al.* 2022; Ragupathi, Barik 2023; Sprouse, Depcik, 2013). However, when the goal is generating usable energy from waste heat, any supplementary power produced can be regarded as an enhancement in overall efficiency. Ongoing experiments have demonstrated a 5% improvement in engine efficiency and an 8% reduction in fuel consumption.

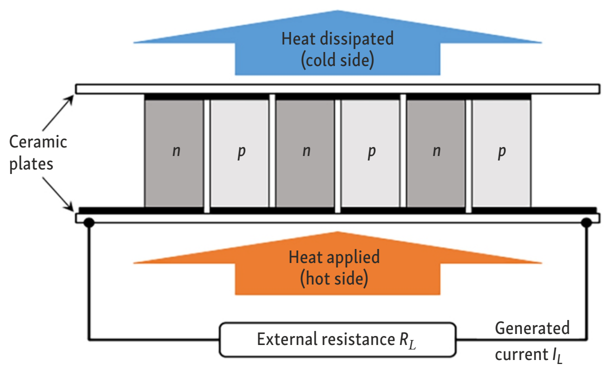

Figure 5. Typical configuration of a thermos electric generator (Konstantinou *et al.* 2022)

The TEG modules presently being developed have an output power of approximately 200 W (Burnete *et al.* 2022; Ochieng *et al.* 2022). Purpose-built heat exchangers with TEG can be utilized at locations where cooling of fluids is already needed, for examples EGR coolers and radiators so that the heat otherwise given off to the environment can be put to use at generating usable energy. The generated electricity of TEG solutions can be utilized as a supplementary power source to reduce loading on the alternator or if efficiency and reliability increases, the alternator as a constant load to the engine can be replaced by a TEG unit. Additionally, TEG modules can be used to heat of cool the surrounding environment by applying a current to the module. This can be used in the heating and cooling of the vehicle cabin to further reduce the parasitic load on the engine and recovering waste heat energy in the process. Further research must be done to increase TEG efficiency, to find suitable materials for the temperature ranges found in ICE and that can withstand the harsh conditions around the engine while it's operating at various conditions (Burnete *et al.* 2022; Ochieng *et al.* 2022; Ragupathi, Barik 2023).

4. FPE

As frictional losses make a large part of losses within an ICE, several alternative technologies are considered to reduce friction within the engine. Friction work in the engine contributes to higher fuel consumption and mechanical losses (Heywood, 2018). FPEs strive to reduce friction and stresses generated within the piston-crank assembly by removing them from the engine and relying merely on the reciprocating movement of the piston within the cylinder. The linear movement of the piston is transferred by mechanical, pneumatic, hydraulic or electric means so that the energy can be harnessed (Jia *et al.* 2018; Raide *et al.* 2017). Ideally this could reduce the frictional loses by 30 to 40% (Heywood 2018; Jia *et al.* 2018). Figure 6 features the main configurations of FPE that include single and multiple piston arrangements and various methods or synchronisation and rebound devices.

One of the best applications for such an engine would be in a LEM, since it would offer the minimal number of moving parts to generate electricity by means of internal combustion (Raheem *et al.* 2022; Raide *et al.* 2017). Simple and compact generator with FPE technology could be fitted to future hybrid vehicles or be used on portable equipment like generators, compressors or pumps (Feng *et al.* 2021; Guo *et al.* 2021; Raheem *et al.* 2022). The FPE is a very versatile machine that has been adopted to operate under various combustion strategies in addition to traditional spark or CI. The ability to alter the CR continuously also allows for different fuels to be used to power the engine (Li *et al.* 2021; Raheem *et al.* 2022).

One of the drawbacks of any ICE is that they need to be kept idling to achieve stable operating conditions even for intermittent loading. In addition, cold starts can bring up problems when certain conditions are not met for optimum combustion to occur. Since the FPE does not have a large flywheel to smoothen out the irregularities while starting or running the engine, alternative approaches must be taken to ease successful cold starts and strategies to deal with misfire that could knock the whole engine out of balance (Raheem *et al.* 2022). Currently stable operation of the FPE and transition between starting, motoring and loading conditions is a matter of interest for many research teams (Feng *et al.* 2021; Raheem *et al.* 2022). Generally, the linear generator of the engine is used to drive the engine until stable combustion can occur (Raheem *et al.* 2022). For reliably starting the engine and transitioning from motored to loaded states needs fast acting control systems (Feng *et al.* 2021). Since piston movement within the cylinder is unrestricted for TDC and BDC positions as it were with a traditional crank assembly, rebound systems are implemented to dampen the movement of the piston (Figure 6). These systems can employ the linear generator, mechanical springs or even pressure of the opposite cylinder to control the movement of the piston during operation (Guo *et al.* 2021; Raheem *et al.* 2022; Raide *et al.* 2017). In addition, precise control of combustion can aid in stabilising the engine and enable a smoother cold start (Feng *et al.* 2021; Raheem *et al.* 2022).

As the engine is running heat is generated that needs to be removed from the engine to avoid damaging the permanent magnets and other components. Of these components the magnets may be the most susceptible to heat damage (Raheem *et al.* 2022; Raide *et al.* 2017). FPE friction work mean values have been lower than that of crank engines in many cases studied (Jia *et al.* 2018; Li *et al.* 2021; Raheem *et al.* 2022). This confirms that the removal of the crank assembly and other mechanism can reduce frictional losses within the engine. But studies focused only on the frictional comparison of FPE and crank

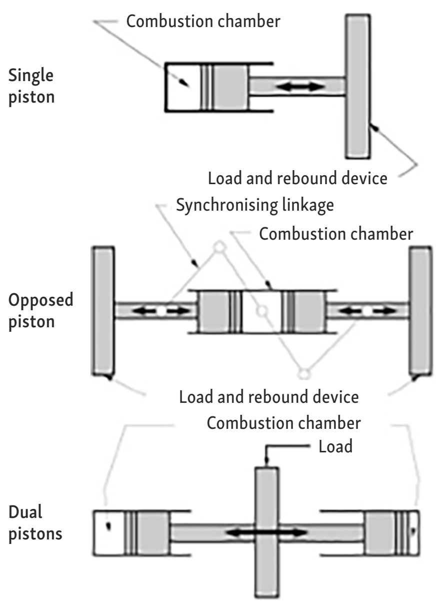

Figure 6. Common FPE configurations – adapted from Jia *et al.* (2018)

engines has shown that FPE piston ring friction is higher (Jia *et al.* 2018; Li *et al.* 2021). Higher friction could lead to more wear of the cylinder liner or piston assembly owing to earlier engine failure.

5. OPE

OPE are another example of ICE technology that was once developed but fell out of use to re-emerge as science and technologies have evolved. The idea to use 2 opposing pistons to increase the expansion ratio while maintaining a shorter crank throw and piston travel is almost as old as the 1st ICE (Gregório, Brójo 2018). Many inventors have patented their designs in the 19th century and even accounts of commercially available vehicles propelled by such engines can be noted. The 1st of these OPE had longer connecting rods to connect pistons mounted on top of the engine cylinders to the single crankshaft situated in the lower part of the engine. One such engine, built by Gobron–Brillié, was able to propel the 1st car over the 100 mph mark; more modern versions having 2 crankshafts were widely used in aviation (Figure 7), military equipment, and transport well into the 1st half of the 20th century but started to fade away and eventually falling out of use (Gregório, Brójo 2018; Pirault, Flint 2010; Young *et al.* 2021).

The OPE has shown great capabilities in CI and SI as well as 2-stroke and 4-stroke configuration and perhaps with modern technologies it could make a comeback. In this spirit contemporary researchers have built proof-of-concept engines by connecting 2 single cylinder engines top-to-top (Gregório, Brójo 2018; Ma *et al.* 2021). This provides an affordable way of doing engine research without the need to build an engine from scratch. Tests conducted by Gregório & Brójo (2018) on a very rudimental OPE built from 2 4-stroke stationary engines already showed an increase in efficiency. Similarly, a 2-stroke OPE was built using motorcycle engines by Ma *et al.* (2021). They implemented more modern technologies including DI (Figure 8). These examples of OPE validated the known advantages of the technology and gave way for further R&D in the field.

In addition to small scale prototypes a full-scale engine has been built by a development team at *Achates Power Inc*. Developments are made both is diesel and gasoline CI technologies (Abani *et al.* 2017; Pirault, Flint 2010; Redon *et al.* 2014; Salvi *et al.* 2022). The developers have also initiated initial road tests in heavy-duty trucks (Fromm 2022).

The higher TE of an OPE stems from a lower surface area for heat losses, relative to the cylinder volume (Abani *et al.* 2017; Redon *et al.* 2014; Salvi *et al.* 2022). This is a result of the engine having no cylinder head as the 2-pistons are positioned at both ends of the cylinder, keeping the heat from escaping. Since the 2-pistons per cylinder move synchronously or only with a slight offset, many of the balancing issues prevalent in a conventional piston engine do not occur (Pirault, Flint 2010; Redon *et al.* 2014; Salvi *et al.* 2022; Young *et al.* 2021). This and the fact that 2-stroke OPE have no need for a valve drive gives the engine even more stability and significantly reduces mechanical losses (Pirault, Flint 2010; Redon *et al.* 2014). 2-stroke cycle also increases the power output and reduces engine size and weight. The 2-pistons per cylinder allow for longer travel along the cylinder without compromising engine top speed or the need for a crankshaft with a long stroke. The longer stroke per cylinder helps with cylinder scavenging, increased air flow, air/fuel mixing and extends the expansion of combustion gasses (Abani *et al.* 2017; Pirault, Flint 2010; Redon *et al.* 2014; Salvi *et al.* 2022).

One of the reasons the production of this type of engine was discontinued lies in the challenges development teams at the time could not overcome. For example, 2-stroke engines have the reputation of having high HC and PM emissions due to engine oil being expelled

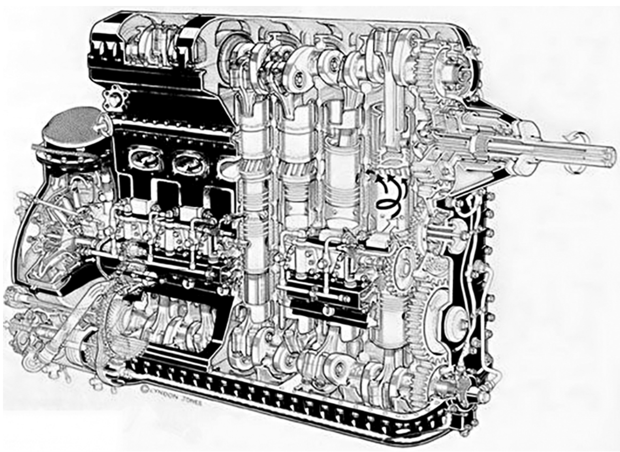

Figure 7. Phantom illustration of the *Junkers 205* OPE (Siadkowska *et al.* 2017)

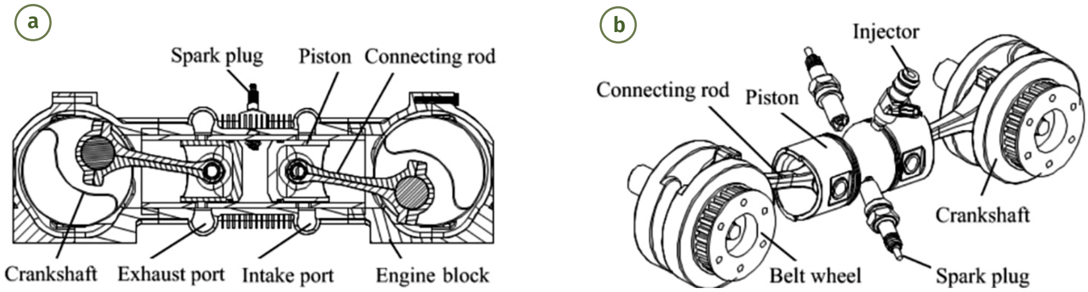

Figure 8. Constructed OPE of Ma *et al.* (2021): (a) – sectional view; (b) – crank assembly

through the exhaust ports. As this also damager catalytic converters, the usage of 2-stroke engines nowadays is only dominant in small and mostly portable equipment or large marine engines (Pirault, Flint 2010). DI engines have the injectors mounted into the cylinder wall and needed very precise spray pattern to not overshoot and hit the opposite wall. To avoid spray impingement novel injector designs are investigated and developed that have spray characteristics intended for OPE use (Ma *et al.* 2021; Zhang, Z., Zhang, P. 2018).

Contemporary simulations and computational capabilities enable researchers to continue where development stopped in the 70s due to OPE technology not meeting the requirements of the time. Modern advances in materials, engine technology and the usage of computerised engine management systems can be used to overcome the shortcomings of the OPE (Abani *et al.* 2017). Advances in turbochargers and superchargers can further improve cylinder scavenging and air flow (Salvi *et al.* 2022). All that R&D is needed to produce a modern OPE that meets all the demands of the end consumer.

6. RE engines

EVs and hybridisation of traditional ICE powertrains has reached the fleet of almost every automotive manufacturer as they seek to reduce their product's impact on the environment. Yet the electric variants are not as popular among the consumers as their ICE counterparts (Duan *et al.* 2021). One of the issues why people shy away from BEV is the relatively low driving range. HEVs of various powertrain arrangement (Figure 9) seek to improve the range of electric powertrains by combining the efficiency and zero tailpipe emissions of an electric motor with the range of an ICE (Veza *et al.* 2020). These REs or REEV are highly efficient ICE coupled with an electric powertrain promises cleaner emissions and reduced fuel consumption (Solouk *et al.* 2017a, 2017b). REEVs recharge the battery on the go and in some cases, provide additional power to the wheels. Since the ICE is generally coupled to a generator, not directly to the wheels the engine can run at a set optimum mode, regardless of the current driving conditions, avoiding the drawbacks of many ICE (Veza *et al.* 2020). As the power demand is shared by the battery and the ICE, the ICE's power can be downsized. Generally, 30…40 kW is regarded sufficient for REEV applications to fulfil the needs of a passenger car to accelerate to highway speeds, with a discharged battery (Borghi *et al.* 2017; Kéromnès *et al.* 2014).

The decoupling of the ICE from directly powering the drivetrain allows for the implementation of various alternative engine technologies like LTC, Wankel engines, FPEs, micro turbines, 5-stroke engines and also fuel cells and many other technologies (Kéromnès *et al.* 2014; Veza *et al.* 2020; Solouk *et al.* 2017a, 2017b). Several of these have proven to be highly efficient and with cleaner emissions than the ubiquitous piston engine found in most motor vehicles. The ideal ICE for a RE application must be compact but with a high-power to weight and volume ratio while still maintaining simple construction and ease of manufacture (Borghi *et al.* 2017; Veza *et al.* 2020; Solouk *et al.* 2017a, 2017b). Although the piston engine is the most prevalent power plant in the field, some researchers have set out to investigate the possibilities of novel LTC technologies in RE applications (Veza *et al.* 2020; Solouk *et al.* 2017a, 2017b). By loading the ICE in a narrow range, the engine can be held at the most efficient condition and the disadvantages of current LTC technologies

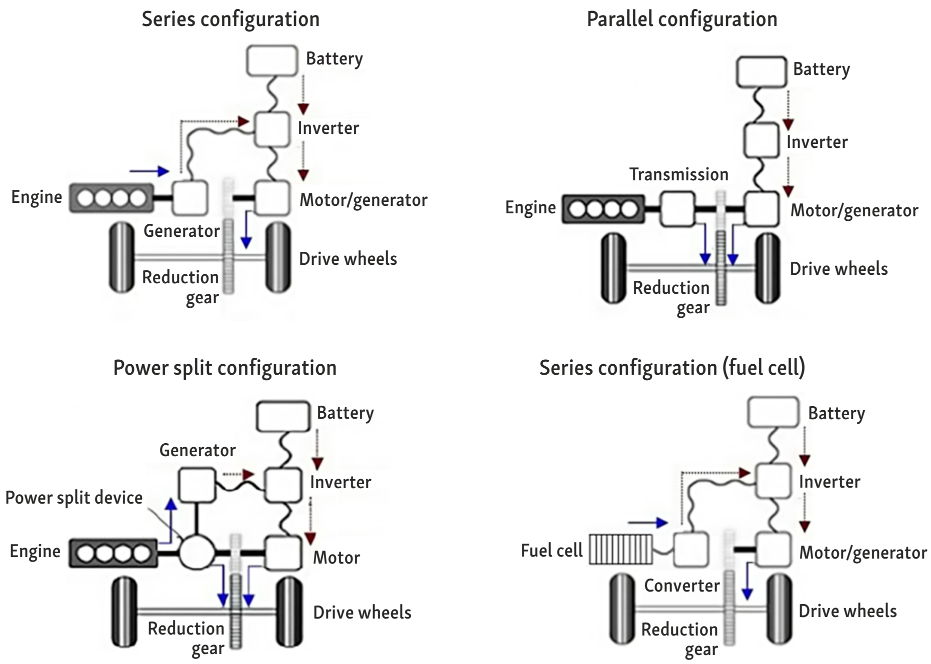

Figure 9. Common powertrain arrangements of hybrid vehicles (Lajunen *et al.* 2016)

can be avoided. Electrical components like the generator have more flexibility and could be engineered to fit the operating conditions specified by the ICE. Implementing different combustion strategies and fuels according to demand and switching the engines settings is also a possible solution. By changing the combustion strategy for various loading conditions, the ICE is running at the optimum mode concerning fuel consumption and emissions (Solouk *et al.* 2017a, 2017b). For most driving conditions there isn't a very high demand for power from the engine so switching to a more conservative LTC mode can significantly lower the environmental impact of the ICE while the battery needs to be charged. During heavy loading for example while the battery is low and the driving conditions require high-power input from the power plants, the ICE can be switched to a higher power mode like conventional SI or CI, that can satisfy both the battery recharge and powertrain demand (Solouk *et al.* 2017a, 2017b). The ICE and electric motor can also work together by blending the output of the 2 engines a technique called torque blending. This way the ICE can stay in LTC mode while the electric motor drives the wheels only when necessary (Solouk *et al.* 2017a).

Converting an existing OEM engine to be a RE may have its benefits regarding cost, reliability, or availability of spare parts, but generally ICE intended for automotive use are too bulky to be fulfil the RE requirement of compactness and high-power density. This has led to R&D of purpose-built RE engines (Figure 10), which allow for selection of solutions and technologies best suited for RE application (Borghi *et al.* 2017; Kéromnès *et al.* 2014).

7. VVA

For 4-stroke engines the opening and closing of valves enables the gas exchange between the intake manifold, cylinder, and exhaust. Historically mechanical poppet valves actuated by a camshaft have been widely used and, in some applications, they are still in use today. The drawback of this generally robust and reliable system is that the valve train can be optimised only for a narrow engine load or speed. This can cause pumping losses outside of the optimum operation range (Pan *et al.* 2021; Wang *et al.* 2021). For modern engines the fixed timing and opening characteristics are not sufficient and more complex systems have been in development since the 1960's. Nuccio & Marzano (2008) have compiled a review of historical variable valve lift and timing systems with various figures that the authors would recommend reading for a good insight into the historical background of VVA. These systems typically involve mechanical or hydraulic mechanisms that allow for adjustments in valve lift or alterations in valve timing based on engine loading conditions. However, it is important to note that these systems, despite their advancements, are ultimately constrained by the cam lobes since they continue to rely on a camshaft for operation (Hannibal *et al.* 2004; Nuccio, Marzano 2008; Pournazeri *et al.* 2018).

VVA is one such technology to overcome the limitations of fixed valve timing and lift (Pan *et al.* 2021). VVA-systems can be categorised as cam-based and camless systems. This depends on whether the valves are actuated by a rotating camshaft or by hydraulic, pneumatic, magnetic or electrical actuators (Pan *et al.* 2021; Pournazeri *et al.* 2018; Tripathy *et al.* 2020a). The later offer more control over opening timing, duration and valve lift to a point where valves can be operated independently from the crankshaft's rotation, enabling cylinder deactivation (Leach *et al.* 2020; Taylor 2008). Cylinder deactivation can be used for engine idling and lower loading scenarios. It reduces the number of fired cylinders in the engine decreasing pumping losses, engine friction and heat losses (Leach *et al.* 2020; Pan *et al.* 2021). These systems have such precise control over the valve opening, that they have the potential to regulate flow into the cylinder, making the use of a intake throttle obsolete (Koenigsegg 2023; Pan *et al.* 2021; Tripathy *et al.* 2020a). Using hydraulic power to actuate the

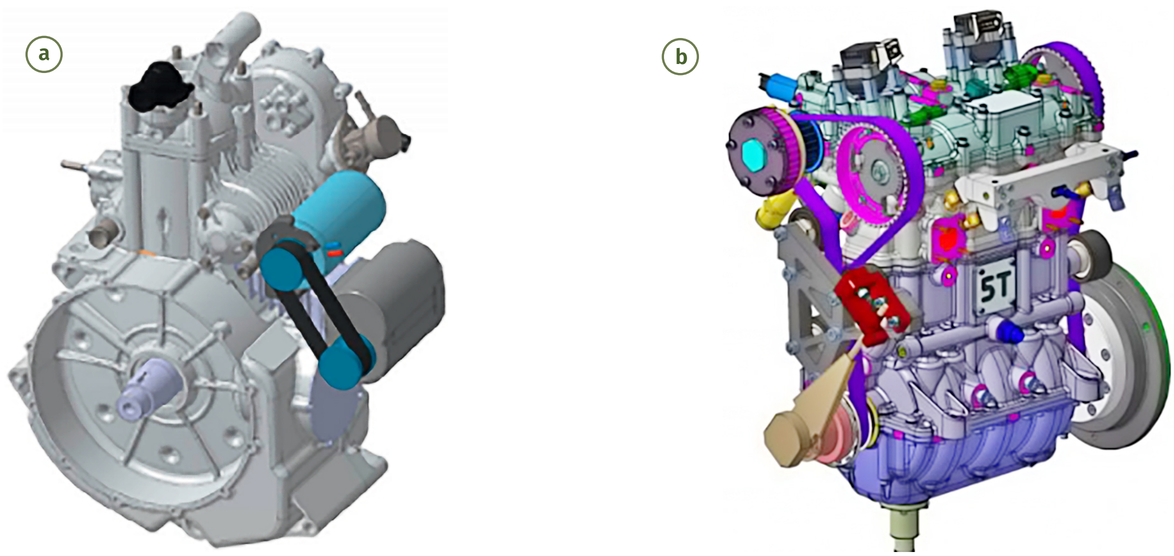

Figure 10. Purpose-built range extender engines by: (a) – Borghi *et al.* (2017); (b) – Kéromnès & Schmitz (Noga 2018)

valves is a likely technology to replace conventional valve trains. One example of this novel design developed by Pournazeri (2012) shows great potential (Figure 11). Their system uses electrically phase shifted rotary spool valves rotated by the crankshaft to control the flow of hydraulic fluid to the valve actuators, allowing for more flexible and precise valve control at various engine speeds (Pan *et al.* 2021; Pournazeri *et al.* 2017, 2018).

A HPSV and a LPSV are used to control oil flow into and from the valve actuator cylinder. These valves ensure precise control over the valve lift and timing. Proper valve seating is ensured by conventional valve springs (Pournazeri *et al.* 2017). Using hydraulic power enables to actuate the valves much quicker than cam-driven valves, allowing for better flow through the valve gaps increasing VE (Pournazeri *et al.* 2017). Usually, a very complex system is associated with bigger power demand that draws energy away from the engine, but for this hydraulic system a recovery system was developed that makes the system use 58% less energy than a conventional camshaft arrangement (Pournazeri *et al.* 2018).

In addition to hydraulic fluids, compressed air can be used in valve actuators. Tripathy *et al.* (2020a) developed an electro-pneumatic VVA-system with a double acting actuator controlled by solenoid valves. Their system allows for precise control of the valves forward and backward motion, eliminating the dangers of high velocity collision of valve and valve seat by using a pneumatic cushioning system.

The developed pneumatic system was tested and compared to a conventional setup with a camshaft and throttle. In an engine test they successfully proved, that VVA can be implemented to replace the intake throttle without any negative effects regarding VE (Tripathy *et al.* 2020b). By varying the valve lift and duration, air flow rate was controlled to suit different engine speeds. Similar VVA-systems to control cylinder air flow have been theorised and tested by other researchers for partial load applications on SI engines (Pan *et al.* 2021; Wang *et al.* 2021). Implementing throttle-less load control serves to increase VE and lower engine pumping losses (Wang *et al.* 2021).

Freevalve is the very 1st VVA-system to reach a production engine in the *Koenigsegg Gemera* hypercar, giving hope that one day this technology might be openly available for regular production cars. This technology uses electro-hydraulic-pneumatic actuators and has no camshaft and thus can employ all the mentioned benefits of VVA (Koenigsegg 2023; Möller 2019).

Current shortcomings of such systems are their complexity compared to conventional cam actuated valve trains, but development may lead to systems that are simple, reliable and affordable enough to be suitable for real-world use (Pan *et al.* 2021; Pournazeri *et al.* 2018). In addition, further research must be done to cushion the high velocity valve seating to mitigate damage done to the valve seats (Pournazeri *et al.* 2017; Tripathy *et al.* 2020a).

8. Variable CR

Engine downsizing and high-pressure turbocharging is a concept being increasingly implemented in SI engine manufacturing due to stricter emissions and fuel consumption regulations (Shaik *et al.* 2007). Then again, a smaller engine must be pushed further to meet the power demand of a modern powertrain. Higher CR has proven to contribute to higher TE and thus higher power as witnessed by CI engines. Theoretically a CR rise from a common SI engine CR 8:1 to 14:1, which could induce knock at higher loading, can increase the efficiency by 15% (Shaik *et al.* 2007).

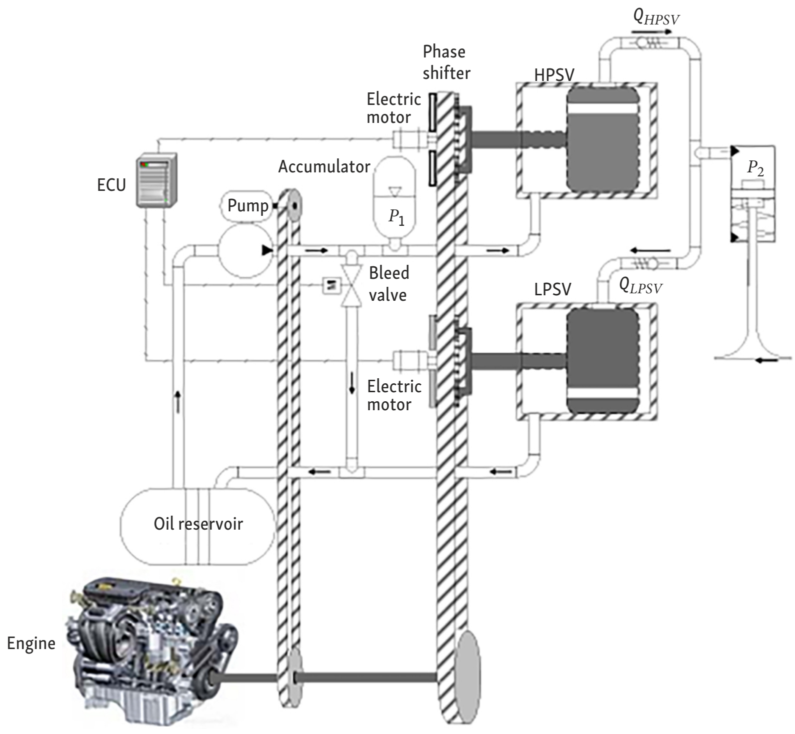

Figure 11. Schematic representation of the VVA-system developed by Pournazeri (2012)

As CR is risen a point of diminishing returns is reached, where the rate of gained power and reduced fuel consumption becomes too small to justify further increasing the CR (Cao *et al.* 2014). Since increasing the CR also increases the restrictive forces in the engine that contribute to a rise in mechanical losses. SI engines are prone to knock at higher loads, due to increased combustion pressure and temperatures in the cylinder, so CR is set lower than with CI engines to prevent engine damage (Heywood 2018; Shaik *et al.* 2007). However, under low or partial loading engine efficiency is lacking since a compromise between knock prevention and efficiency is made. Ideally, an SI engine should have a higher CR during low and partial loading to increase TE and the ability to switch to a lower CR during high loading scenarios to prevent knock and maintain high efficiency. Various LTC strategies could also benefit from VCR since it gives better control over the pressure and temperature within the combustion chamber (Agarwal *et al.* 2017; Alagumalai 2014; Duan *et al.* 2021).

To combat knock at higher loads and poor efficiency at low loading scenarios, various solutions have been proposed and developed to vary the CR of ICE according to engine loading. Many experimental engines have been built and tested for many decades but as of 2019 the automobile manufacturer Nissan has managed to develop the 1st multi- link VCR turbocharged production engine (De Bortoli Cassiani *et al.* 2009; Hiyoshi *et al.* 2006; Hoeltgebaum *et al.* 2016; Hiyoshi *et al.* 2006).

The technologies and mechanisms used to vary CR can broadly be categorised as follows:

- moving the crankshaft (Envera LLC 2018; Shaik *et al.* 2007);
- using a multi-link system (Hiyoshi *et al.* 2006; Milojević *et al.* 2018);
- moving the cylinder head (De Bortoli Cassiani *et al.* 2009; Shaik *et al.* 2007);
- altering the connecting rod geometry (Cao *et al.* 2014; Fraidl *et al.* 2016; Wittek *et al.* 2019);
- varying the piston deck height (Shaik *et al.* 2007; Wittek *et al.* 2019);
- changing the combustion chamber volume (Guan *et al.* 2021; Shaik *et al.* 2007).

8.1. Moving the crankshaft

One method to alter the CR in an engine is moving the crankshaft rotational axis relative to the cylinder head (Envera LLC 2018). By moving the crankshaft, the position of piston TDC is changed allowing for more room within the combustion chamber for lower CR or less room for higher CR. This can be considered a non-invasive approach, since the majority or engine components can be similar or the same as a conventional production engine. Resulting in lower cost of manufacturing. To alter the position of the crankshaft it is mounted in an eccentric carrier or cradle (Figure 12) that can be rotated by an actuator mechanism to achieve continuously variable CR (Envera LLC 2018; Shaik *et al.* 2007).

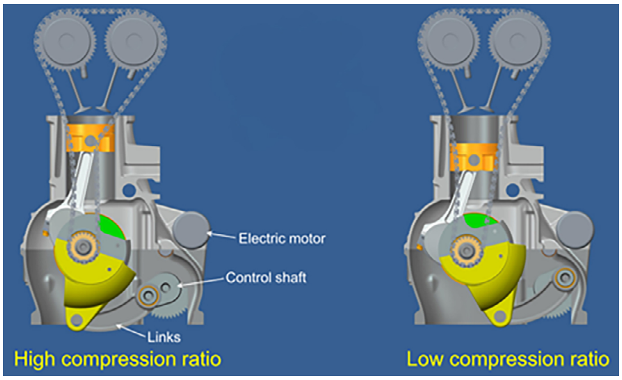

Figure 12. VCR mechanism developed by Envera LLC (2018)

The merits of such a mechanism are the ease of manufacture but also, since the reciprocating assembly is unaltered, no additional mass is added to the system. This can lower the risk of secondary vibrations and no added friction is added. The downside of this system is that since the crankshaft needs to be connected to a transmission or output device to deliver power, an additional fixed shaft needs to be coupled to the moving crankshaft (Shaik *et al.* 2007).

8.2. Using a multi-link system

Conventional piston engines have only one link between the crankshaft and piston, but some VCR engine designs utilise a multi-link system to alter the length of the connecting rod or crank throw (Cao *et al.* 2014; Hiyoshi *et al.* 2006; Milojević *et al.* 2018; Shaik *et al.* 2007; Wittek 2006). Incorporating a multi-link system into the reciprocating assembly of a conventional engine needs only minor alterations, meaning that no larger scale modifications to production lines and existing engines must be made. As far as the authors know, this method is the only example of a VCR engine that has reached production (Figure 13). Therefore, some actual data from testing prior to the final version of *Nissan*'s engine is briefly presented.

The earlier results published in 2006 showed great promise of an engine suited for production not just R&D (Hiyoshi *et al.* 2006). The VCR engine was based on a production engine of similar build; therefore, engine test results could be adequately compared. As a result of multiple engine tests, the researchers concluded that the prototype had an overall power increase of 10%. Higher power at higher loading was achieved with a lower CR setting, which enabled to utilise higher boost pressures and a larger turbo A/R ratio. At non-turbocharged regions and lower loading, a 13% reduction in fuel consumption was observed. In addition, the EGR limit was expanded.

Analysis of the mechanism revealed that the motion of the piston is slower near TDC, yet faster near BDC. Since the piston accelerates slower at TDC as the base engine many advantages emerged. Reduced piston acceleration means that stress acting on the assembly is reduced and time for combustion is increased aiding in a more complete combustion near TDC. Unfortunately, this also keeps the combustion pressure high for a longer period and measured piston blow-by was higher compared to the base engine. The higher combustion gas temperature and pressure contributed to increased cooling losses, but other losses were in turn smaller and so the effect was cancelled out.

Other authors have found that adding complexity to the crank assembly introduces more mass and friction. Consequently, adding inertia and unwanted vibrations to the moving assembly (Shaik *et al.* 2007; Wittek 2006). The researchers at Nissan measured frictional losses and discovered, that the multi-link assembly kept the upper link connected to the piston upright and thus piston slap vibrations and friction between the piston, piston rings and the cylinder liner was significantly lower than the reference values of a conventional engine. Thus, ultimately all smaller increases in overall losses were cancelled out by larger advantages of the developed multi-link system. In summary the prototype was successful in eliminating the shortcomings of a fixed CR SI engine and in addition one of the biggest sources of friction and engine wear was also decreased.

8.3. Changing the combustion chamber volume

As VCR technology relies mainly on altering the volume of the combustion chamber one approach to consider would be to do exactly that. For this a small secondary chamber is added to the cylinder head that can communicate with the main chamber via a valve or moving piston (Shaik *et al.* 2007). By implementing this technology, only a redesign of the cylinder head is needed, meaning a large portion of the engine block and moving assemblies will remain untouched. Changing the available combustion chamber volume can be considered passive or active. Passive meaning that the volume is changed by a valve allowing for gases to flow between the 2-chambers. With active volume control the volume is dynamically altered and allows for continuous variability of the CR. A orifice between the 2-chambers allows for gasses to move along a pressure gradient (Guan *et al.* 2021). Of the 2 the active version would be preferable since this mitigates problems like carbon build-up and promotes scavenging of the auxiliary chamber, thus reducing trapped residual gases. The engine built by Guan *et al.* (2021) involves a small reciprocating piston situated in the cylinder head. This piston is connected to the valve train and is placed opposite to the main piston (like the OPE). In addition, this secondary piston has the ability to generate additional power from the combustion process, within the range of 2…9% (Guan *et al.* 2021). Overall fuel consumption was reduced due to an improved effective expansion efficiency. A rise in combustion peak pressure near TDC contributed to increased TE providing greater power output.

Testing confirmed that the ignition of the mixture in the auxiliary chamber was induced by the stream of high-pressured hot gasses and radicals from the initial combustion in the main chamber. This was observed to be similar to the combustion process in TJI and produced an almost complete combustion in the 2nd chamber. The phenomenon is not without drawbacks, seeing as the slender passage can quench the hot flame front and thus inhibit combustion in the 2nd chamber. Moreover, crevice quenching especially at higher CR settings showed a rise in HC emissions. Likewise, since combustion is happening within the cylinder head, cooling losses are increased due to a larger heat transfer into the head (Guan *et al.* 2021; Shaik *et al.* 2007). Therefore, packaging of the cylinder head must consider additional cooling and lubricating of the secondary reciprocating assembly. Future iterations of such systems need to account for these issues to increase flow between the 2-chambers while also allowing room for 4-valves, a sparkplug and DI.

8.4. Altering the connecting rod geometry

An alternative approach to multi-link systems are connecting rods that have a variable geometric length (Fraidl *et al.* 2016; López *et al.* 2020; Shaik *et al.* 2007; Wittek 2006; Wittek *et al.* 2019). This system features a fairly simple design that could be implemented in any engine with minimum modifications to the original engine. The idea lies in altering the effective length of the connecting rod and by this moving the piston TDC position up or down. This is

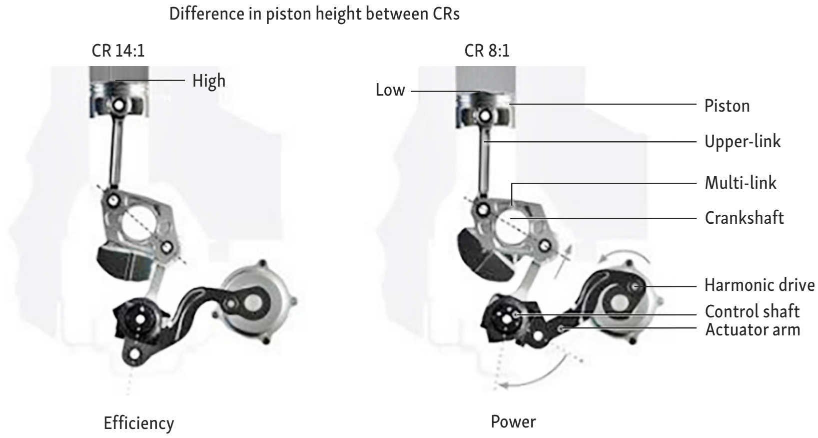

Figure 13. Schematics of the VC-T engines multi-link assembly (Milojević *et al.* 2018)

achieved mainly by a modified connecting rod that with the help of hydraulic pressure from the engine oil pump can push out a telescopic actuator in the shank of the connecting rod or rotate an eccentric bushing on one or both ends of the connecting rod (Fraidl *et al.* 2016; Wittek 2006). Within the connecting rod are hydraulic components that depending on change in oil pressure or combustion pressure and inertia of the moving assembly can switch the rod assembly between a low and high setting via hydraulic actuators as shown in Figure 14.

At lower loads, the engine oil and combustion pressures are generally lower so this warrants one effective length. Under load and at higher engine speeds the pressures are higher and so are the forces acting on the reciprocating mechanism. These conditions trigger the switchover to the lower CR position.

As this is a self-regulating system, no continuous varying of CR is used and the CR is switched between 2-stages. As a result, the ratio between low and high CR must be smaller than with continuously variable systems to reduce the risk of problems in the intermediate engine speeds and loads. During part-load conditions CR can be switched either way due to the fluctuating forces acting on the assembly. Furthermore, the switchover process can last many engine cycles (up to 1 sec) so engine mapping must account for the conditions in between 2 states (Wittek *et al.* 2019). Lastly, some concerns over the longevity of the engine oil due to high-pressures induced in the hydraulic system have been voiced. Although in some of the designs cavitation and high-pressures could occur, solutions to many problems have been claimed to be found (Wittek 2006; Wittek *et al.* 2019).

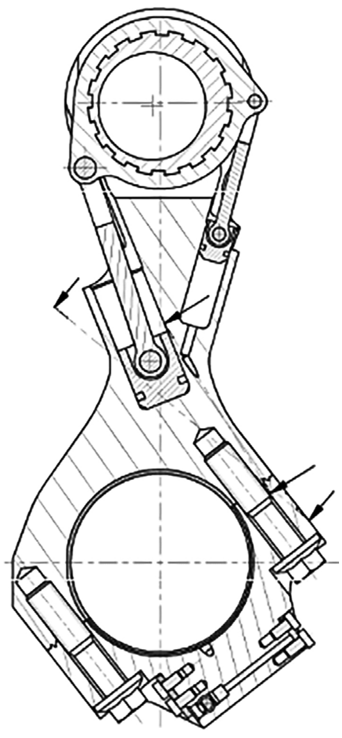

Figure 14. Cross-sectional view of a VCR connecting rod developed by Wittek (2006)

8.5. Varying the piston deck height

One of the 1st attempts to develop a variable compression engine was done using pistons that would alter their deck height depending on the combustion pressure. Such a piston was developed by the British Internal Combustion Engine Research Institute (UK) and successfully tested in multiple research labs and engines (Ashley 1990).

The technology behind varying the piston deck height is comparable to the previously discussed connecting rod with varying length. The piston is made of 2 parts (Figure 15), the middle part (3) is attached to the connecting rod (6). This middle section is surmounted by a larger piston (2) that similarly to a conventional piston communicates with the combustion chamber and has piston rings to sea against the cylinder walls. Depending on the specific version a combination of hydraulics or springs is used that pushes against the outer piston to increase the piston deck height and in turn to increase the CR (Shaik *et al.* 2007). At higher loads and consequently higher combustion pressures, the gas forces working against the force from the mechanism are greater and thus the piston deck height is lowered. This design and some fine adjustments lead to that a preferable CR is always selected for the current loading conditions (Shaik *et al.* 2007; Wittek 2006).

Until now, the focus in this section has been only on SI engine but variable compression can be beneficial to CI engines as well. The main reason to vary the CR in CI engines is to limit peak combustion pressure at high loads to reduce strain on the engine. Teledyne Continental Motors was successful in almost tripling the power output of a tank engine by implementing these pistons (Ashley 1990; Shaik *et al.* 2007).

The technology has many advantages over some of the more complex systems covered in this topic. For one it has

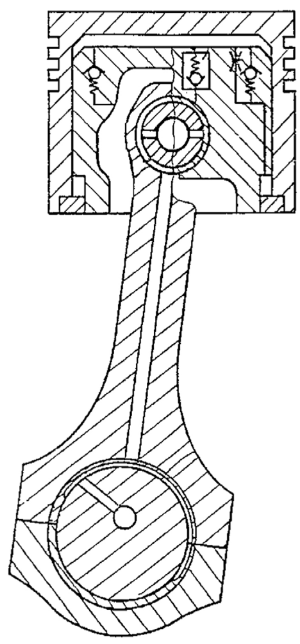

Figure 15. Patent figure of variable deck height piston developed by *Daimler-Benz AG* (Pfeffer, Wirbeleit 1988)

minimal impact on a conventional engine regarding production, so theoretically only the piston and connecting rod need to be modified, retaining the majority of components. This could save in costs regarding redesigning production lines and engines, which is one of the commercial application barriers that has hindered adaptation of VCR in mass production (Shaik *et al.* 2007). Retrofitting VCR kits to existing engines would also be an option.

Although this version of VCR is quite simple in design and easy to implement in conventional engines it has many drawbacks that have inhibited further R&D in the recent years. Since this is a self-regulating system no direct control over the CR is given so the effect of the variable piston is not comparable to continuously variable systems. Thus, the only benefits are reduced peak pressures during combustion that protects the engine from knock or high strain. The complex structure of the piston needs additional balancing due to different materials used in the VCR mechanism. Thermal losses and hotspots in the piston could also be a problem. In addition, there is a constant relative movement of the 2 major piston parts, which brings additional vibrations, slack and ultimately wearing into the reciprocating assembly. The inherent flaw in the working principle of the mechanism can cause a temporary increase in CR during a sharp spike in pressure induced by combustion, which is later decreased during the expansion process, leaving less volume for the expanding gasses (Shaik *et al.* 2007).

Together, the presented systems show a promising piece of technology that could further help to reduce the harmful effects of ICE on the environment and aid in the search for ever cleaner propulsion systems.

9. LTC strategies

9.1. LTC

LTC is a combustion concept that blurs the lines between conventional SI and CI engines by employing strategies from both technologies. The fundamental principle lies in achieving complete combustion of a homogeneous lean mixture. The combustion is generally initiated by an auto-ignition event of the mixture that promotes a low combustion temperature and moderate combustion pressure peaks (Agarwal *et al.* 2017). A majority of the LTC strategies rely on the pressure and temperature history of the combustion chamber to induce ignition, but there is one exception that is TJI.

9.2. Pre-chamber ignition (TJI)

Recent technological developments have enabled ICE to reach new heights in efficiency, but SI engines have yet to reach the same level as CI engines. Globally SI engines are dominating the passenger car market, meaning their efficiency must improve (Ershov *et al.* 2021). The lower efficiency lies in the way a SI engine operates. Due to the properties of the fuel used, knock can easily occur, so many methods are employed to mitigate knock from occurring, but these methods also limit the engines TE. Compared to a CI engine the mixture is much richer to ensure proper ignition and combustion of the mixture (Heywood 2018). A leaner fuel–air mixture is difficult to ignite with a point ignition system like the sparkplug. Therefore, research is under way to adopt a novel space ignition system called TJI to SI engines (Zhu *et al.* 2022).

Contrary to previous pre-chamber combustion systems developed in the past, in TJI the pre-chamber is relatively small compared to the clearance volume of the cylinder and connected to it not via a throat-like opening but multiple smaller orifices (Figure 16) (Alvarez *et al.* 2018; Bianco *et al.* 2020; Boretti 2020; Dilber *et al.* 2022).

Recently this technology has gained momentum, as the manufacturer *MAHLE Powertrains* revealed a TJI system that could be feasible for commercial use (Leach *et al.* 2020; Zhu *et al.* 2022). Until now a passive version of this technology has been used in motorsport, but not on road cars (Bianco *et al.* 2020; Boretti 2020).

The ignition and combustion principle of TJI differs for conventional practises. Although a sparkplug is used to ignite a rich mixture of fuel and air, this mixture is ignited within the small pre-chamber. For passive systems, fuel injection only occurs in the main chamber. The premixed (homogeneous) charge is then pushed into the pre-chamber during the compression stroke through the orifices. Active systems have one injector placed into the pre-chamber (Figure 16) and another in the main chamber to form a lean mixture (Alvarez *et al.* 2018; Zhu *et al.* 2022) The small dimensions of the pre-chamber ensure, that only a small amount of fuel is needed to form a rich (stratified) mixture near the sparkplug, which can easily be ignited. As the mixture combusts a rapid build-up of pressure forces the burning mixture out of the pre-chamber. The rest of the charge within the cylinder can be direct or port injected and kept very lean. Even to a point where it would not ignite by applying conventional ignition methods. For TJI, combustion in the main chamber is initiated by turbulent jets of high-pressure flames propagating from the pre-chamber orifices. As these highly turbulent jets of flames propagate into the main chamber, they promote active

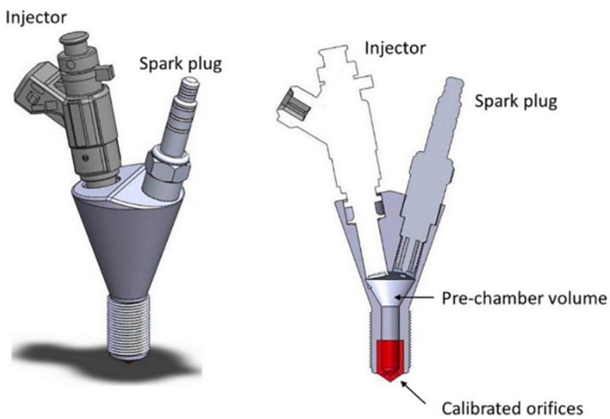

Figure 16. Active pre-chamber TJI unit designed to fit into a standard spark plug hole by Boretti (2020)

mixing of the cylinder content and combustion of the lean charge. The subsequent combustion occurs throughout the cylinder similarly to a SI engine's premixed flame (Tolou 2019; Zhu *et al.* 2022).

Recent R&D of TJI has shown many advantages to this technology to improve current SI engines. Engine tests on TJI have shown that implementing space ignition can increase the knock limit of an engine allowing for higher CR to be used and the efficiency to increase (Hua *et al.* 2021; Tolou 2019). Many researchers have studied this phenomenon and reached the conclusion that due to the end gas burning off before combustion reaches a point where knock can occur knock tendencies diminish. Moreover, the inherently lower combustion temperature and pressure reduced knock significantly (Alvarez *et al.* 2018; Hua *et al.* 2021). This allows TJI engines to run on lower ON fuels and utilise the benefits of a higher CR, the later aiding in improving TE. Higher CR are needed for passive TJI systems to promote pre-chamber scavenging and filling (Zhu *et al.* 2022).

Since the current trend is to design the jet injection unit so that it may fit into the sparkplug hole of any SI engine, retrofitting of this technology could be used to improve engines already in use or ease the implementation of the technology in production cars with minimal changes to production lines (Hua *et al.* 2021).

Test results of Hua *et al.* (2021) and other researchers indicated that the superior mixture ignition capabilities of TJI enable lean and ultra-lean mixtures to be used (Alvarez *et al.* 2018; Hua *et al.* 2021; Soltic *et al.* 2021). Testing has shown that lambda values of 1.5 to 1.6 with petrol and even higher values with gaseous fuels or dual fuel application can be achieved (Alvarez *et al.* 2018; Soltic *et al.* 2021). It was concluded that lambda values up to 1.5 could easily be achieved without an active pre-chamber, while using petrol fuel (Hua *et al.* 2021; Soltic *et al.* 2021). Emissions wise a decrease in NO_x was observed by many researchers. This was accredited to lower combustion temperatures and rapid combustion not providing the conditions for NO_x development (Alvarez *et al.* 2018; Hua *et al.* 2021). In some studies, ultralow or near zero NO_x emissions were achieved. TJI runs at lean combustion resulting in more oxygen to be available for the fuel to react with. This substantially lowers CO emissions (Alvarez *et al.* 2018). Better mixing due to more turbulent air movement in the main chamber also contributes to more efficient combustion and lower CO values in the exhaust (Hua *et al.* 2021). In addition to a lower combustion temperature, the laminar flame speed in higher, thus combustion duration is shorter. As the jet travels with great speed into the main chamber, it can reach a larger portion of the mixture in a shorter time and ignite it. The HRR and the cylinder pressure of TJI has a more rapid rise to the peak than conventional SI engines. After the peak the values descends rapidly at the end of combustion. The many staged of combustion measured by Hua *et al.* are due to the mixture 1st combusting in the pre-chamber and then entering the main chamber where a 2nd wave of combustion occurs. This is in contrast to conventional SI where the mixture combusts from a single point and thus the pressure rise and HRR have a smoother progression (Hua *et al.* 2021; Soltic *et al.* 2021).

A shorter combustion leads to lower heat losses since the flame burns our before hitting the cylinder walls and the combustion products have less time to give of heat the engine. This lowers heat losses and increases TE.

The size and shape of the pre-chamber and the size, number, angle, and location of nozzle holes in the pre-chamber play a key role in the combustion characteristics and engine performance and efficiency. Various studies indicate that although there are some general guidelines to follow, the best results are gained when a nozzle is designed specifically for the engine in question (Alvarez *et al.* 2018; Hua *et al.* 2021; Zhu *et al.* 2022). Regarding the size of the pre-chamber, different values are mentioned, but generally the size is around 10% of the main chamber volume (Alvarez *et al.* 2018; Zhu *et al.* 2022). Smaller pre-chambers have the advantage of needing less fuel mass to ignite, so more of the fuel per cycle can be kept it the main chamber. Since the pre-chamber generally sits within the cylinder head less heat is dissipated into the head when a smaller pre-chamber is used and heat losses are reduced (Alvarez *et al.* 2018; Hua *et al.* 2021). Studies concentrated on the pre-chamber orifices generally do not show a common trend. Hua *et al.* concluded in their study that fewer holes in the pre-chamber give greater spray velocity, the jet is less likely to be quenched and the jet is generally stronger (Hua *et al.* 2021). Whereas other studies and CFD modelling indicates that, while keeping the cross-sectional area constant, more orifices increased turbulence within the chambers and granted better mixing (Alvarez *et al.* 2018; Zhu *et al.* 2022).

Although TJI is a promising technology, with greater efficiency and lower fuel consumption and emissions, there are yet some challenges for researchers to tackle before it can be fully implemented in production engines.

As one of the design directions is to place the TJI unit into the cylinder head where a sparkplug would conventionally be, new problems emerge. Due to the combustion happening in the pre-chamber, a lot of heat is generated that dissipates into the cylinder head (Zhu *et al.* 2022). The cylinder head is not built to be so close to combustion and therefore current head designs lack the cooling to divert the heat from the combustion. New cylinder head designs must be developed to accommodate the TJI unit in a way that heat losses are reduced using new material to direct the heat away from the head or increase cooling where needed. The issue lies not only in heat loss, but also in irregular combustion. If the TJI unit is not sufficiently cooled glow ignition could occur leading to uncontrolled combustion (Zhu *et al.* 2022). Damage to the sparkplug and injector may also occur due to excessive heat. In a conventional SI engine combustion is triggered from a central point in the cylinder and a flame front propagates radially outward and generally the fuel has combusted before the front reaches the cylinder walls. With TJI the combustion is initiates at the edge of the combustion chamber since the orifices are situated at the border of the 2-chambers (Zhu *et al.* 2022). As combustion is initiated at the outer rim of the combustion chamber, the flame front is more likely to be quenched by the cylinder wall. This leads to higher HC emissions in some cases studied (Alvarez *et al.* 2018; Zhu *et al.* 2022). Flame quenching is also more common due to thermal quenching of the small pre-chamber, where the hot radicals are more likely to hit the chamber wall or come into contact with the orifices (Zhu *et al.* 2022). Crevice effect is also an issue as there is a more complex volume of chambers for the mixture to travel in. However, the turbulent jets do not even have to come to contact with any wall as hydrodynamic quenching from the jets mixing with the colder charge in the main chamber can occur (Zhu *et al.* 2022). Lastly there is an issue with fuel injectors (Zhu *et al.* 2022). The miniscule amounts of fuel delivered to the pre-chamber demand for more precise injector to be developed that can cope with smaller fuel flow rates, withstand the conditions in the pre-chamber and be compact enough to fit within the TJI unit.

9.3. HCCI

HCCI is a combustion engine variation where there is no direct control over the timing of ignition and combustion of the mixture. This is because no sparkplugs or injection of additional fuel into the mixture is used to bring the mixture to combust (Duan *et al.* 2021).

1st attempts to utilise chemical-kinetics controlled combustion were in the 1930's by Russian scientist Semenov; in the 1970's the 1st auto-ignition engine, the avalanche activated combustion engine, was built by Gussak; later Onichi developed the active-thermo atmosphere combustion and Noguchi the *Toyota-Soken* combustion concept; over time various concepts were developed built and investigated, until Najt and Foster built their 4-stroke engine employing the concept they named compression ignition homogeneous charge, laying the way for LTC technologies in the future (Agarwal *et al.* 2017; Duan *et al.* 2021; Gussak *et al.* 1975; Noh, No 2017).

In HCCI the fuel and air are generally introduced into the engine prior to compression and form a homogeneous mixture, hence the name. The required activation energy for combustion to occur is achieved solely by the pressure and temperature within the cylinder (Agarwal *et al.* 2017; Duan *et al.* 2021; Hasan, Rahman 2016). The mixture combusts, contrary to traditional SI and CI engines, not from a centralized point from which a flame front protrudes to ignite the whole mixture, but at various point through-out the combustion chamber as illustrated by Figure 17.

This simultaneous auto-ignition of the mixture results in a homogeneous oxidation of the fuel that promotes a cleaner combustion and higher efficiency (Duan *et al.* 2021; Polat *et al.* 2020). HCCI engines can operate at very lean conditions and are quite fuel flexible (Bendu, Murugan 2014; Duan *et al.* 2021; Khandal *et al.* 2017). Lean combustion is achieved due to the fact that the fuel auto-ignites, thus no rich region near a sparkplug is needed to initiate ignition. Moreover, contrary to conventional CI no fuel rich region is formed as a result of fuel directly injected into the cylinder. As pockets of rich mixture contribute to soot formation, lean HCCI engines have the potential for low PM emissions (Alagumalai 2014; Khandal *et al.* 2017; Noh, No 2017). In addition, since the lean fuel mixture combusts at multiple sites simultaneously, no local regions with high temperature emerge. This and the fact that combustion temperatures are lower than with conventional engines contributes to ultra-low NO_x emissions (Agarwal *et al.* 2017; Khandal *et al.* 2017; Noh, No, 2017). Simultaneous combustion at multiple sites means that combustion duration is shorter since multiple ignition sites have flame fronts propagating outward, speeding up the chain reaction (Agarwal *et al.* 2017). Lower combustion temperatures and shorter combustion duration near TDC significantly reduce heat loss and increase TE as fuel is burned at near constant volume and less time is available for heat dissipation.

HCCI is unfortunately not without limitations. Due to the narrow window of optimal conditions for auto-ignition to occur, advanced techniques and methods must be implemented to sustain the ideal temperature, pressure, and combustion history in the cylinder. Particularly during cold starts and varying loading conditions (Polat *et al.* 2020; Solouk *et al.* 2017b). Engines take time to warm up during cold starts particularly at lower ambient temperatures. Once they have warmed up the thermal mass of the engine makes it difficult to rapidly make changes to

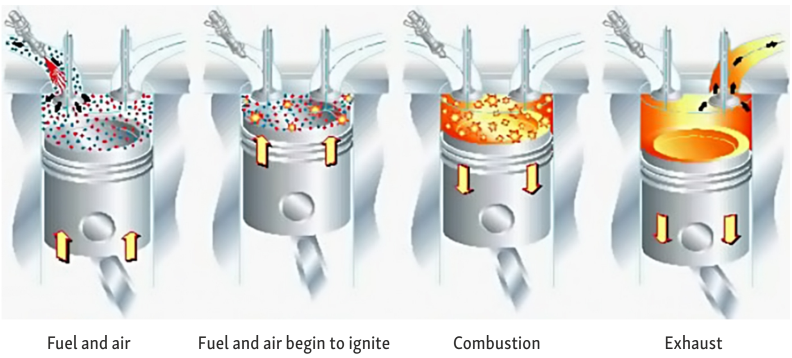

Figure 17. Principle of HCCI shown in a 4-stroke cycle (Ryan, Matheaus 2003)

engine temperatures. Since HCCI is dependent on engine temperature, real life conditions currently hinder widespread usage (Hasan, Rahman 2016). As HCCI engines are capable of operating at very lean mixtures, inducing ignition demands optimum conditions for auto-ignition to reliably occur (Agarwal *et al.* 2017; Bendu, Murugan 2014). Deviation from the optimum will result in unpredictable ignition timing and combustion, unwanted combustion phasing and occurrence of excessive engine noise and knock (Duan *et al.* 2021; Khandal *et al.* 2017). Furthermore, fuel particles in the lean homogeneous mixture are more spread out. Giving way for crevice effect and fuel film build-up on engine components (Bendu, Murugan 2014; Duan *et al.* 2021). This leads to incomplete combustion and an increase in CO and HC emissions (Duan *et al.* 2021; Khandal *et al.* 2017; Noh, No 2017). The lower combustion temperature is not sufficient to complete CO to CO_2 formation and to burn off any unburned charge that is stuck in the crevices or away from the main combustion zone (Hasan, Rahman 2016; Khandal *et al.* 2017; Mofijur *et al.* 2019). Moreover, the temperature of exhaust gasses is inadequate for exhaust gas after treatment systems to properly reduce emissions further along the exhaust path (Agarwal *et al.* 2017).

Start of combustion and combustion characteristics can be controlled by adjusting a number of engine parameters. Table 1 gives an overview of the effects of altering these parameters.

Many of these approaches are a mix of several methods and some cannot be implemented alone. This is not a definitive list and additional methods are implemented to control HCCI combustion characteristics and engine efficiency and power. For example, to overcome the limitations of HCCI at cold starts and at high loading modes, dual-mode operation has been proposed as a solution (Agarwal *et al.* 2017; Kalghatgi 2005; Khandal *et al.* 2017; Solouk *et al.* 2017b). Dual-mode operation utilises conventional SI or CI technologies at moments where HCCI cannot operate as needed. For example, during warm-up conventional combustion technology can be used to provide suitable conditions for LTC technologies.

In addition to these engine parameters, various fuelling strategies can be used to modulate the strength and homogeneity or stratification of the mixture. As well implementing dual fuelling, fuel blending, alternative fuels and fuel additives can be used to control combustion characteristics.

HCCI was one of the 1st LTC concepts to be developed, however ideal conditions for a completely homogeneous charge to auto-ignite are difficult to achieve. As shown is Table 1 a number of strategies are applied to enable optimum combustion at a wide range of engine modes. As a result of this various derivatives of LTC have emerged that exercise many of the techniques applied with HCCI to gain similar results. The following paragraphs cover these LTC concepts.

9.4. PCCI

PCCI or PPC is a new combustion strategy currently being researched that promises better TE and lower emissions (Bobi *et al.* 2022). Contrary to conventional compression ignition where fuel is injected before TDC and mixed with air as it auto-ignites, PPCI uses an early pilot injection to prepare a lean homogeneous air-fuel mixture during compression that is later ignited by a main injection (Yin *et al.* 2018). The mixture burns cleaner due to better mixing with oxygen. Also due to the wider spread of fuel in the cylinder, the peaks of combustion temperature and HRR are lower, providing for a more evenly distributed release of combustion energy, through this strategy a preferred LTC condition is achieved (Bobi *et al.* 2022). Lowering combustion temperature is a key ingredient in reducing NO_x emissions and raising TE (Bobi *et al.* 2022). Using various techniques to mitigate uncontrolled combustion, enables the use and combining of various fuels that previously were unsuited for compression ignition, opening the opportunity for GDCI (Sellnau *et al.* 2016).

To make PCCI commercially viable, scientific work is conducted to study how choice of engine characteristics, fuels and their blend contribute to a more stable combustion during various loading scenarios while maintaining optimum fuel efficiency and low emissions. Some studies focus on altering engine characteristics like injection timing and pressure, CRs, piston bowl shape and intake air temperature and EGR content. Others take their aim at fuel properties like ON and CN. Mixing fuels and using additives to alter fuel properties is also an important research direction (Bobi *et al.* 2022).

As PCCI is quite similar to HCCI similar problems emerge and control strategies are used to ensure desired combustion characteristics. Injection timing is the main factor influencing combustion in PCCI engines. An advanced injection gives more time for mixture building but if the mixture spread-out is too wide, it can also lead to wall wetting, which leads to incomplete combustion. Fuel meeting the walls and getting into chamber crevices causes high HC emissions due to the flame front not meeting the mixture as well as poor mixing in crevices and droplets condensing on cylinder walls result in combustion with insufficient oxygen creating high CO emissions (Bobi *et al.* 2022; Chumueang *et al.* 2015; Izadi Najafabadi *et al.* 2017). Injecting too late resembles regular CI where a large portion of fuel auto-ignites rapidly due to highly turbulent mixing and this results in a sharp rise in HRR contributing to NO_x formation due to high temperatures (Bobi *et al.* 2022; Izadi Najafabadi *et al.* 2017).

Typically a higher CR is associated with higher efficiency but can also cause knock to occur (Bobi *et al.* 2022; Heywood 2018). Lowering CR in PCCI engines decreases premature auto-ignition of the mixture by increasing ignition delay. Yet again there is a delicate balance to hold because lowering the CR also results in lower cylinder temperatures meaning incomplete combustion and higher

Table 1. Methods of controlling combustion in HCCI engines

Engine parameter	Method	Effect on combustion characteristics	Drawbacks
Valve timing and lift	trapping exhaust gas in the cylinder with VVA, negative valve overlap or exhaust rebreathing (Agarwal *et al.* 2017; Duan *et al.* 2021; Khandal *et al.* 2017; Polat *et al.* 2020)	▪ increases initial mixture temperature, fuel vaporisation, HRR; ▪ decreases cyclic variations, knock, combustion duration, combustion temperature, minimum CR requirements	higher temperatures induce knock and advanced ignition
CR	Utilising high CR (Agarwal *et al.* 2017; Duan *et al.* 2021)	▪ increase fuel reactivity, air-fuel mixing, combustion stability, cold start capability, cylinder temperature, efficiency, lean burn range; ▪ decreases inlet temperature requirements, combustion duration	higher CR advances combustion and increases combustion pressure, at higher loading knock can occur; fuels with low ON can't be used
	Utilising low CR (Khandal *et al.* 2017; Polat *et al.* 2020)	▪ increases possibility of higher boosting pressures and VE, operation range at higher loading, injection advance; ▪ decreases knocking tendency, combustion pressure rise rate, ignition advance	lower CR impedes the use of fuels with low reactivity
	Utilising VCR to reduce or increase the CR according to engine mode (Duan *et al.* 2021)	▪ increases low to high loading range, increases temperature and pressure at TDC; ▪ decreases initial charge temperature requirements, knock at higher loading, cyclic variations	some VCR technologies are not capable of individual cylinder control required by multi-cylinder engines
Inlet temperature	Preheating the charge with engine waste heat or an electric heater (Agarwal *et al.* 2017; Bendu, Murugan 2014; Duan *et al.* 2021; Noh, No 2017)	▪ increases low load operation range, fuel vaporisation, in-cylinder temperature, cyclic stability, ignition advance; ▪ decreases requirements for auto-ignition (high CR, etc.), emissions by improving combustion, misfire	preheating the air reduces VE so boosting is needed to compensate for that
Inlet pressure	Boosting the inlet pressure with a supercharger or turbocharger (Bendu, Murugan 2014; Duan *et al.* 2021; Polat *et al.* 2020)	▪ increases VE, mixture homogeneity through increased turbulence, peak combustion pressure, combustion advance, simultaneous combustion, engine knock tendency, engine high load operation range and range of operation of sensitive fuels; ▪ decreases effective CR required to facilitate auto-ignition conditions	engine mechanical CR is limited due to the danger of knock
Injection strategies	PFI (Agarwal *et al.* 2017; Duan *et al.* 2021; Khandal *et al.* 2017)	▪ increases mixing time and homogeneity of the mixture ▪ decreases VE, ignition delay, in-cylinder temperature	fuels with low volatility can't be injected early due to wall wetting and crevice effect
	DI (Agarwal *et al.* 2017; Bendu, Murugan, 2014; Duan *et al.* 2021; Khandal *et al.* 2017; Polat *et al.* 2020)	▪ increases control over ignition timing, stratification of the mixture, VE; ▪ decreases cycle-to-cycle variations, required fuel volatility	high-pressure and early injection can cause impingement of cylinder walls and lubricant dilution
Use of EGR	Introducing exhaust gases into the cylinder (Agarwal *et al.* 2017; Duan *et al.* 2021; Khandal *et al.* 2017)	▪ increases ignition delay (when cooled), high load range, fuel vaporisation, combustion duration, high load range, mixture dilution; ▪ decreases knock probability, fuel reactivity, rapid pressure rise, combustion temperature	using EGR as a diluent can induce incomplete combustion and increase emissions of CO and HC

HC and CO emissions (Bobi *et al.* 2022). Dual fuel options could be the solution by using a high ON fuel for premixing and a more reactive fuel for the main injection. High ON will help to increase the ignition delay and a reactive fuel will more readily initiate ignition after injection (Bobi *et al.* 2022).

To reach an optimally high cylinder temperature while still maintaining a lower CR one can heat up the cylinder content by means of an external heat source. This is particularly important for fuels, which require a high temperature to auto-ignite.

9.5. RCCI

RCCI uses 2 fuels to accomplish a controlled combustion process in which a low reactivity (high ON and low CN) fuel is premixed prior to compression and a high reactivity (low ON and high CN) fuel is directly injected into the cylinder at the desired timing to initiate combustion as illustrated on Figure 18 (Alagumalai 2014; Li *et al.* 2017).

RCCI can be viewed as a further development of HCCI by applying dual-fuel strategies for ignition and combustion control. Therefore, many similarities in engine char-

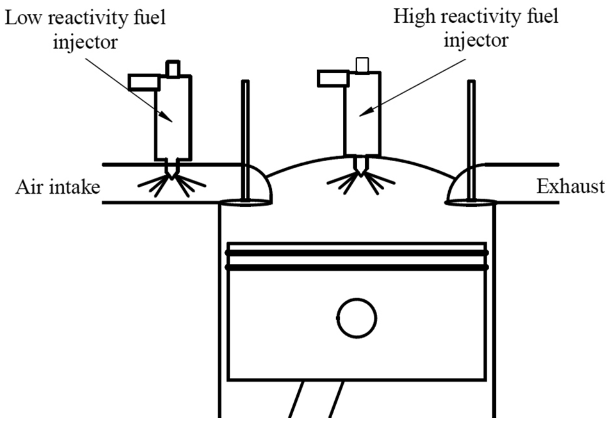

Figure 18. Schematic principle of injector layout in RCCI (authors' own work)

acteristics and control mechanisms can be seen. However, there are some differences in RCCI that may give it an advantage over previously discussed LTC strategies.

For one, having a highly reactive fuel as the ignitions source for the whole mixture has its advantages over HCCI that mainly relies on the chemical-kinetics of the mixture for auto-ignition and combustion to occur as desired (Paykani *et al.* 2021). Keeping optimum auto-ignition conditions over varying engine loads can be a delicate balancing act. With RCCI combustion is initiated similarly to a conventional DI CI engine, so combustion timing and phasing is easier to manage (Li *et al.* 2017). Since RCCI is a dual fuel technology, the different reactive properties can be implemented so that by adjusting the ratio of fuels the engine maintains its high efficiency and near zero NO_x and soot emission throughout a wide range of engine speeds and loads (Lee *et al.* 2022; Li *et al.* 2017; Singh *et al.* 2021). Mineral diesel fuel is widely used as the high reactive fuel in RCCI studies and the low reactive fuel can be a standard liquid or gaseous fuel or an alternative fuel (Ashok *et al.* 2022; Lee *et al.* 2022; Li *et al.* 2017; Singh *et al.* 2021).

Introducing a premixed charge into the cylinder prior to DI can alter the combustion characteristics, but the results vary from fuels injected and the ratios used. Engine tests conducted by Singh *et al.* (2021) using diesel and petrol showed that the premixed charge can have a cooling effect on the charge and slow down the chemical-kinetics of the charge, thus increasing ignition delay. The combustion was observed to be smoother than conventional CI and lower combustion pressure peaks were measured. Test results indicated that operation at RCCI mode increased the TE of the engine. Lee *et al.* (2022) used diesel and methane gas to fuel a RCCI engine and concluded that introducing a premixed methane charge into the cylinder reduces ignition delay and combustion duration, advanced combustion and increases HRR.

Dual fuelling gives the engine fuel flexibility and many studies with various alternative fuels have been conducted (Ashok *et al.* 2022; Chakraborty *et al.* 2022; Li *et al.* 2017; Paykani *et al.* 2021). In some studies, using biofuels has shown better combustion characteristics and reduces emissions. These renewable fuel sources further increase the environmental friendliness of the highly efficient RCCI engine. However, some say, that as alternative fuels are not widespread around the world, more traditional fuels would warrant a better global reception if RCCI engines were to reach production. For this reason and the fact that using multiple fuels needs separate fuel tanks and thus takes up more room, some researchers have proposed blending fuels with additives that can alter the reactivity of a fuel (Ashok *et al.* 2022; Li *et al.* 2017). By injecting the neat and blended fuel and different locations, desired RCCI conditions could be created. Unfortunately, currently single fuel RCCI engines struggle with emissions and stability issues.

Research has shown that increasing the PFI ratio can reduce NO_x emissions (Li *et al.* 2017). This can be explained by the combustion characteristics of homogeneously premixed charge. This is contrary to DI, where fuel rich pocket occurs, promoting the build-up of soot due to insufficient oxygen. Altering the fuel ratios gives for a smoother combustion as the mixture combust with milder pressure rise rates than conventional combustion technologies, thus providing for less knocking tendencies (Li *et al.* 2017). Injection strategies have a strong influence over the start of combustion and the course of burning in RCCI as concluded in many studies (Ashok *et al.* 2022; Li *et al.* 2017). Some researchers have even proposed dual DI solutions, also called direct dual fuel stratification, that reduce the HC and CO emissions (Li *et al.* 2017; Elbanna *et al.* 2022). The advantages of dual DI lie in reducing the disadvantages witnessed by PFI that come from crevice effect and wall wetting and local low reactivity areas. In addition, the timing and volume of the injected fuel gives more control over the combustion phases.

The piston bowls of conventional CI engines are designed to improve mixing of air and fuel but for RCCI the charge is premixed so other designs are developed to better suit the mixing and combustion characteristics of RCCI engines (Li *et al.* 2017). As many researchers have proposed that RCCI engines could be operated as a conventional combustion engine during transient loading and high-power demand, the piston design must accommodate for both modes (Li *et al.* 2017; Solouk *et al.* 2017b).

With many merits of the RCCI engine, there are still some aspects that need further research. Similarly, to other LTC engines RCCI also displays higher HC and CO emissions due to drawbacks of lower combustion temperatures and longer mixing times (Ashok *et al.* 2022; Li *et al.* 2017; Singh *et al.* 2021). Many of the combustion control methods mentioned in Table 1 must also be utilised in RCCI to keep the knocking tendencies down and gain a more reliable and stable combustion at varying conditions and engine modes (Lee *et al.* 2022; Li *et al.* 2017; Paykani *et al.* 2021).

9.6. Commercial viability of LTC technologies

LTC technologies have many merits when it comes to combustion efficiency but are still lacking in combustion stability and reliability that is necessary for commercial applications. ICE used in passenger cars are subject to varying environmental and loading conditions and the vehicle must be capable to operate according to the driver's inputs. As LTC engines are mainly operable in their optimum range, alternative approaches must be considered to adapt this technology.

Combining conventional combustion strategies with LTC could be one solution. Engine tests conducted by Polat *et al.* (2020) indicated that for high-power demanding scenarios switching to conventional SI can be more feasible as more power can be reliably generated. In this context, *Mazda* has developed their *SkyActiv-x* production engine that operates with spark-controlled compression ignition. The engine is equipped with sparkplugs to facilitate ignition under conditions in which combustion is difficult to achieve with CI (Barba 2018; Ershov *et al.* 2021; Johnson, Joshi 2018). Similarly, Solouk *et al.* (2017a, 2017b) studied the feasibility of LTC engines as a RE for hybrid drives. They concluded that during higher power demand a dual-mode solution gives more flexibility in a HEV. Both research teams concluded that utilising LTC concepts in hybrid drives could be a way to make them feasible in production cars due to the relatively steady loading of engines in HEV applications.

Owing to their high overall efficiency and low fuel consumption they outperform conventional ICE in steady state loading scenarios. However due to their lower power output and problems ensuring reliable combustion during transient loading, a dual-mode engine is needed to support the power demand under circumstances where high wheel and battery power is required (Paykani *et al.* 2021; Solouk *et al.* 2017b).

LTC being a new technology has new requirements for fuels. This means that standard fuels might not be suitable for HCCI and similar engine technologies but also gives way for alternative approaches (Duan *et al.* 2021). Fuels used in HCCI engines must be volatile, to facilitate fast and sufficient mixing (Kalghatgi 2005). Low volatility and high boiling point fuels like diesel fuel for example are not suitable for external charge preparation as they do not form a good homogeneous mixture when injected into low temperature air. This leads to uneven mixing with very lean zones and also very rich zones. As a result, uneven combustion occurs and an increase in HC and NO_x emissions and the build-up of soot follows (Kalghatgi 2005). However, diesel fuel has good auto-ignition properties when directly injected into the cylinder before TDC as the temperature and pressure are higher. Thus, for DI strategies it is a feasible solution. High volatility fuels like petrol on the other hand could cause knock when injected into such conditions. Petrol and other high volatility fuels are used mainly for external mixing as they evaporate much readily at lower temperatures providing a good homogeneous mixture. Adjusting the ratio of high and low reactivity fuels in the cycle gives control over the combustion phasing and ignition timing (Agarwal *et al.* 2017). As mentioned previously, standard fuels alone are not suitable for LTC applications to provide a smooth combustion process over a wide range of engine modes. To enhance the chemical properties of standard fuels they are blended (Kalghatgi, 2005). Introducing fuels with lower reactivity or higher ON into the mixture has the benefit of controlling ignition delay, combustion phasing and peak pressure rise rates (Duan *et al.* 2021). This can be used to lower the knocking tendency of fuels like petrol and enables to widen the engine operation range and increase power output. Some of these additives like ethanol can be used as an independent fuel as well (Noh, No 2017).

Ethanol contributes to stabilising combustion of fuels due to it having anti-knock properties like high ON, high temperature of auto-ignition and high heat of evaporation (Noh, No 2017). Furthermore, ethanol can be sourced by environmentally friendly means, making it a biofuel, which can aid in the lowering of global green gas output.

However high volumes of energy must be used to refine ethanol from a watery solution during production and due to the hydroscopic nature of the alcohol water can be later introduced into the fuel. Be it pure ethanol or a blended fuel, as both are available on the market, fuel water content is not an issue for HCCI applications as concluded by many researchers (Duan *et al.* 2021; Noh, No, 2017).

Water is used as a diluent to lower fuel reactivity by thinning out the mixture and drawing heat from the charge (Agarwal *et al.* 2017; Duan *et al.* 2021). Water can be introduced into the cylinder as fuel emulsions or sprayed during mixture forming. The effects of water are prolonged ignition delay and combustion and lower combustion temperatures. To lower the energy consumption of ethanol dehydration experiments with wet ethanol have been conducted (Noh, No, 2017). Testing has shown that by implementing heated intake technologies ethanol of up 40% water by volume can be efficiently used to fuel HCCI engines. Some problems with combustion efficiency need further investigation, but the overall energy saving of using wet ethanol directly as a fuel is a welcome idea to contribute to a greener future of transportation in the same way as LTC technologies have a great potential to provide greater efficiencies to internal combustion.

10. Summary of recent developments in piston engine technology

In Table 2, a summary of all the technologies covered by this article is presented highlighting the advantages, shortcomings and efficiency values of individual engines.

As witnessed by this summary there are many promising ICE technologies being developed that may lead to commercially feasible solutions, which provide highly efficient and more environmentally friendly propulsion systems to power vehicles and industry around the world.

Table 2. Summary of novel ICE technologies

Technology	Advantages	Drawback	Efficiency
5-stroke engine	▪ less heat losses through exhaust gases; ▪ up to 18% recovered engine power	▪ fixed high efficiency points; ▪ negative pressure in the exhaust manifold during low loading	▪ efficiency gain compared to similar 4-stroke engine; ▪ +36.1% overall efficiency (Palanivendhan *et al.* 2016); ▪ +13% TE (Noga, Sendyka 2014); ▪ +17% total efficiency (Noga, Sendyka 2014)
6-stroke engine (with direct water injection)	▪ higher VE; ▪ WHR	▪ low freezing point of water; ▪ water damage to the engine	▪ an 12.61% TE increase with water injection compared to without water (Arabaci *et al.* 2015)
WHR with ORC	▪ reduced heat losses through exhaust gases; ▪ increased power; ▪ direct electricity generation for auxiliary devices	▪ bulky systems with long lasting processes (industrial applications more feasible); ▪ working fluid toxicity	▪ 12.5% overall efficiency increase compared to unmodified engine (Vaja, Gambarotta 2010)
Free piston	▪ higher power to volume and weight ratio; ▪ lower friction; ▪ variable CR	▪ piston travel and engine stability difficult to control; ▪ lubricating and cooling systems need development work	▪ engine efficiency 50% (Guo *et al.* 2021); ▪ engine efficiency 31...34% (Veza *et al.* 2020)
Opposed piston	▪ 12% lower manufacturing costs compared to conventional piston engine (Pirault, Flint 2010); ▪ lower heat losses owing to no cylinder head used	▪ fuel spray impingement; ▪ HC and PM emissions of 2-stroke engines	▪ 55% BTE (Abani *et al.* 2017); ▪ 47% ITE (Zhang, Z., Zhang, P. 2018); ▪ 30% TE (Ma *et al.* 2021); ▪ 42% BTE (Pirault, Flint 2010)
RE	▪ fixed operating points for optimum efficiency; ▪ light and compact	▪ intermittent operation hinders catalytic converter light-off; ▪ LTC technologies have a lower power output	▪ depends on the engine technology implemented
VVA	▪ precise control over valve lift height, timing and duration of individual cylinders; ▪ no throttle needed, thus lower pumping work; ▪ increased gas exchange efficiency	▪ reliability and endurance testing pending; ▪ valve seating must be cushioned due to high velocity	▪ 5.43% increase in ITE at partial loading thanks to reduced pumping and mechanical losses and increased volumetric and combustion efficiency (Wang *et al.* 2021)
VCR	▪ increased efficiency; ▪ lower losses; ▪ reduced knock	▪ requires redesigning traditional engine layouts; ▪ adds complexity to the engine	▪ 10% increase in BTE as CR was increased from 10 to 15 (Pandey, Kumar 2022)
TJI	▪ increased knock limit; ▪ increased TE; ▪ lower emissions	▪ new cylinder head design required to accommodate TJI unit and its cooling; ▪ flame quenching prominent; ▪ novel injector designs needed	▪ BTE reached 40% during testing (Soltic *et al.* 2021; Tolou 2019)
HCCI	▪ higher efficiency; ▪ low NO_x and PM emissions	▪ cold starting and transitional loading conditions problematic; ▪ knock at higher loading	▪ 45% BTE (Khandal *et al.* 2017; Noh, No 2017); ▪ 39% BTE (Solouk *et al.* 2017b)
PCCI	▪ good mixture preparation; ▪ fuel flexible	▪ traditional fuels are not suitable for optimum performance	▪ 50% ITE (Bobi *et al.* 2022)
RCCI	▪ low NO_x and PM emissions; ▪ fuel flexible	▪ dual fuelling adds complexity and takes up space in the vehicle	▪ BTE 40% (Li *et al.* 2017); ▪ BTE 38% (Solouk *et al.* 2017b)

11. Potential concept to investigate: the membrane engine

11.1. Construction and working principle

The 1st half of this article focused on design modifications to the traditional arrangement of the piston engine. Different approaches were taken and for some the purpose of redesigning the piston engine was to reduce the drawbacks of the piston assembly associated with friction, wear, and the resultant power loss. One method to consider is replacing the piston in the cylinder with a resilient membrane. Using a membrane (diaphragm) instead of a piston could have many benefits that could result in an engine that is more efficient and releases less pollutants into the environment. Over the years many patents of so-called membrane engines have been drawn-up but no known documentation of engine prototypes being built, or engine test conducted has been published (Figure 19) (Breitgraf 1988; Hupkens 1986; Meschendörfer 1989; Werding 2007).

Because similar technology is used as membrane (diaphragm) pumps in automotive and industrial applications, similarly as piston compressors are comparable with piston engines, a possibility of a membrane engine in probable (D'Amico *et al.* 2018; Jia *et al.* 2016; Li *et al.* 2020).

Likewise, the working principle of a membrane engine has several similarities to a piston engine. These likenesses in the construction and operation enable the description of several processes in the membrane engine using the theories and models of reciprocating engines.

Figure 20 describes the working principle of the membrane engine according to the 4-stroke Otto cycle. The process begins with the intake stroke as the fresh mixture is pulled into the combustion chamber by the membrane that is pulled downward by the crank assembly. After which the mixture is compressed and ignited by a spark plug. As the bottom of the combustion chamber is sealed from the crankcase by means of an elastic membrane, the expanding combustion gases push against this membrane, and it is pushed down, similarly to a piston. Opposed to a piston the membrane does not move, it only flexes downward and can also be stretched to increase the stroke. As the membrane is at BDC the maximum volume of the combustion chamber is achieved at the end of the power stroke. The combustion gases are pushed out during the exhaust stroke that ends at TDC where the membrane is flexed and/or stretched upward giving the minimum volume.

The gas exchange of the combustion chamber can be governed by a conventional valve train or a novel VVA approach that could also allow for a 2-stroke working cycle yielding higher engine power per engine cycle.

11.2. Theoretical advantages and possible disadvantages

Replacing the piston in a reciprocating engine with a resilient membrane could potentially remove some of the shortcomings of the piston assembly. For one, there is high wear and friction between the piston, piston rings and cylinder lining. The assembly is one of the biggest source of engine frictional losses and require constant lubricating of the cylinder liner to reduce wear. Contemporary LTC strategies could gain from this technology as potentially lower frictional losses yield a higher power output. Patents of the membrane engine refer to a much simpler and lighter engine, thus further showing application possibilities as a LTC RE engine for steady state loading (Breitgraf 1988; Meschendörfer 1989).

Secondly, the precision-made parts of the piston assembly must fit together seamlessly to seal the combustion gasses within the cylinder and avoid piston blow-by (Breitgraf 1988; Gargate *et al.* 2014; Hupkens 1986; Kim *et al.* 2012; Meschendörfer 1989; Werding 2007). Similarly, the piston rings must keep engine oil from seeping into the combustion chamber and unburnt fuel from reaching the crankcase. Engine oil in the combustion chamber will increase exhaust gas smokiness and unburnt HC emissions of the engine and encourage the build-up of carbon on the engine components. The carbon layer disrupts the normal function of valves reducing engine power and can also increase wear on the moving parts of the engine as they become dislodged and soil the engine oil (George *et al.* 2007). Increased wear of the cylinder liner and piston promotes additional blow-by and also allows for more unburnt fuel and other contaminants to slip by the piston rings and end up in the engine oil. Lighter HCs from the fuel dilute the oil and further reduce the lubricating capabilities of the engine oil. Completely sealing the com-

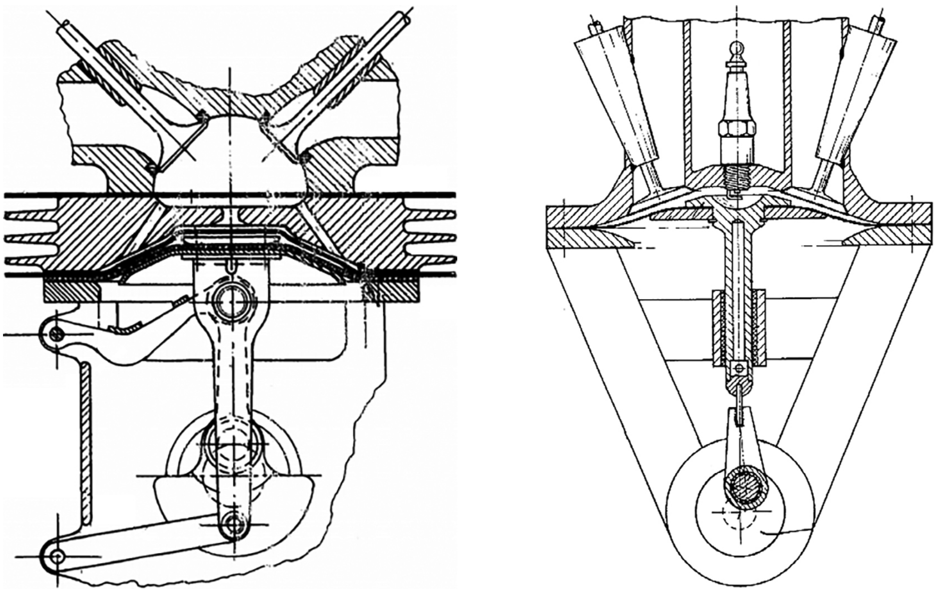

Figure 19. Outtakes of membrane engine drawings from published patent documents (Hupkens 1986; Meschendörfer 1989)

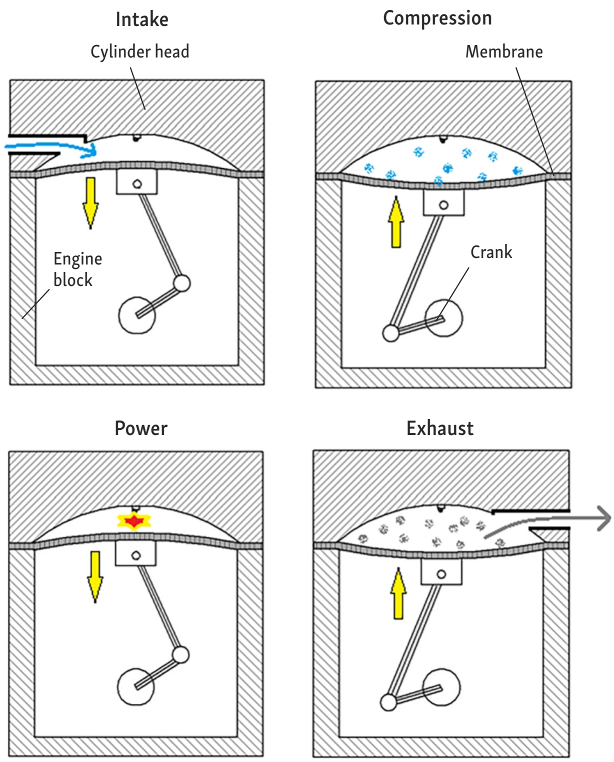

Figure 20. Principle drawing of the membrane engine throughout the 4-stroke working cycle (authors' own work)

bustion chamber from the crankcase could mitigate the soiling of engine oil and prevents oil from entering the combustion chamber. This feature could also be beneficial for engines where water injection is used to increase WHR. Be it an external cylinder of a 5-stroke engine, the main combustion chamber of a 6-stroke engine or any other WHR solution, the superior sealing capabilities of a membrane will prevent water and gasses from seeping out of the chamber.

In theory, the membrane could solve some problems associated with piston engines and the reciprocating assembly, but new challenges are sure to emerge as new developments always give unforeseen results. The 1st hurdles to overcome are tied to the material of the developed membrane. The material must withstand high-pressures and temperatures with contact to volatile chemicals while still remaining resilient. For this, the WHR approach can be taken and direct contact to combustion can be avoided. Initial testing and modelling must be done to assess the forces within the membrane engines reciprocating assembly to determine whether a decrease in mechanical losses compared to an equivalent piston engine can be achieved. This also is related to the materials used since different materials can be stretched or flexed with varying force and amplitude. Research must be conducted to determine whether the forces needed to bring the membrane into the BDC position are truly lower than the frictional forces within the piston assembly, as claimed by previous patent authors. In addition, the potential energy stored with in the membrane under tension during the TDC and BDC positions could result in a totally different moving characteristic of the crank assembly that needs thorough investigation as problems from rapid velocity spikes within the assembly can emerge.

Witnessed by the many patents published, there might be great potential in the membrane engine and for this reason a prototype must be constructed and tested to see whether there is any truth in the claims proposed by the authors of the patents and the authors of this article.

12. Conclusions and future prospects

This article presents a comprehensive review of contemporary innovations in internal combustion technologies in development and production. Scientists today face many challenges for the future that they seek to overcome. With no doubt the emissions regulations will become more stringent and solutions to improve combustion engines need to be investigated. LTC is one prominent technology that could aid in meeting the future regulations and combined with alternative engine design concepts and powertrain hybridisation future transport could be greener in many ways. Currently investigated technologies implemented on traditional piston engines yield noticeable efficiency gains and reduce their emissions considerably, but more scientific work must be done to bring the ICE another step further.

It would be encouraged for future research to broaden their research by investigating novel ideas and revisiting old ideas and implementing not one but many of the technologies featured in this article. For example, for the technologies that are most efficient only at fixed loading and engine speeds, like the 5-stroke engine and some LTC strategies, could be utilised for hybrid drivetrains as electric power generation can be optimized according to the ICE characteristics. Similarly, HCCI and comparable technologies could greatly benefit from the possibilities of VVA and VCR to gain better control over the combustion process and warrant better performance under varying conditions. In addition, all combustion engines expel hot and high-pressure combustion gasses and have a need to be cooled during their operation. This energy should not be simply given off to the environment but harnessed for power generation through various WHR technologies currently under development. The combination of different technologies will surely increase the efficiency of the ICE as a whole and thus reduce their negative effects on our environment.

Surely, the replacement of a combustion engine for alternative propulsion systems might happen in some fields of its wide range of usage but for the foreseeable future a total retirement of the ICE is not feasible. Currently many alternatives to the ICE are in development and some have reached public use. However, governed by the reluctance to change by the public, the transfer to an alternative means of transportation means that the cars built today will still be on the roads for the coming decades. Additionally, the infrastructure must accommodate any new alternative to a level where the end consumer will find it acceptable to transfer to an alternative fuel or powertrain. In the meantime, let us hope that progress in the field of ICE R&D will find better and better ways to reduce the negative effects it has on the environment.

Author contributions

Roland Allmägi collected data and drafted the article.

Risto Ilves supported the workgroup with knowledge of ICE theory and research methodology.

Jüri Olt consulted the team on patent research matters.

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