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Conventional and Insulated Pulse Diesel Engines Performance and Combustion

Alaa El-Din Mohamed M. Ibrahim

Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

Abstract: Internal combustion engines are most commonly used for mobile propulsion in vehicles and portable machinery. In mobile equipment, internal combustion is advantageous since it can provide high power-to-weight ratios together with excellent fuel energy density. Diesel engines and HCCI (Homogeneous Charge Compression Ignition) engines rely solely on heat and pressure created by the engine in its compression process for ignition. The compression level that occurs is usually twice or more than a gasoline engine. Diesel engines take in air only and shortly before peak compression, spray a small quantity of diesel fuel into the cylinder via a fuel injector that allows the fuel to instantly ignite. HCCI type engines take in both air and fuel, but continue to rely on an unaided auto-combustion process, due to higher pressures and heat. This is also why diesel and HCCI engines are more susceptible to cold-starting issues, although they run just as well in cold weather once started. Light duty diesel engines with indirect injection in automobiles and light trucks employ glow plugs that pre-heat the combustion chamber just before starting to reduce no-start conditions in cold weather.

Key words: Performance · HCCI Engine · Diesel Engine · Combustion Chamber

INTRODUCTION

Engines Can Be Classified in Many Different Ways: By the engine cycle used, the layout of the engine, source of energy, the use of the engine, or by the cooling system employed. The Common layouts of engines are: Reciprocating (Two-stroke engine, Four-stroke engine, Six-stroke engine, Diesel engine, Atkinson cycle and Miller cycle) Rotary (Wankel engine) and Continuous combustion (Gas turbine and Jet engine (including turbojet, turbofan, ramjet, Rocket, …etc.).

There is an ongoing effort to improve fuel mileage in motor vehicles. In the last half century, fuel mileage improvements from internal combustion engines have most often resulted from volumetric efficiency improvements (i.e.: increased peak horsepower per unit volume of cylinder displacement) rather than thermal efficiency improvements. Fuel mileage gains have come by way of increased strength and horsepower of engines, allowing smaller displacement engines to be installed into larger vehicles where they are tasked to operate within a more thermally efficient segment of their operating range. Fuel mileage improvements can become tougher to achieve as small displacement engines more routinely populate large vehicles [1].

Some Common Engines: Atkinson engines, which are found in some of today's most fuel efficient cars, achieve improved thermal efficiency through an expansion process which reduces volumetric efficiency and which expels less heat energy to the exhaust duct than equivalently powered Otto engines. HCCI engine development programs, now popular in laboratories around the world, achieve improved thermal efficiency through a combustion process which reduces volumetric efficiency and which expels less heat energy to the exhaust duct than equivalently powered Otto and Diesel engines. Atkinson and HCCI engines suggest some thermodynamic processes with reduced volumetric efficiency and cooler exhaust gas temperature can provide a pathway toward improved engine thermal efficiency and vehicle fuel economy.

It is well known fact that about 30% of the energy supplied is lost through the coolant and the 30% is wasted through friction and other losses, thus leaving only 30% of energy utilization for useful purposes. In view of the above, the major thrust in engine research during the two decades has been on development of low heat rejection engines. Several methods adopted for achieving low heat rejection to the coolant were using ceramic coatings on piston liner and cylinder head and

Corresponding Author: Alaa El-Din Mohamed M. Ibrahim, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt. E-mail: amibrahim1962@yahoo.com.

creating air gap in the piston and other components with low-thermal conductivity materials [2-3], However, this method involved the complication of joining two different metals. Dhinagar *et al.* [4] used different crown materials with different thickness of air gap in between the crown and the body of the piston. Ceramics have a higher thermal durability than metals; therefore it is usually not necessary to cool them as fast as metals. Low thermal conductivity ceramics can be used to control temperature distribution and heat flow in a structure [5].

The Insulated Pulse-combustion Engine and Some Benefits: The "insulated pulse-combustion engine", sometimes abbreviated "insulated pulse engine" or "IPC engine", is a reciprocating piston engine concept which explores five pathways of non-productive energy export from internal combustion engines (thermal conduction, exhaust heat, exhaust pressure, exhaust pollution and mechanical losses), with the goal of providing fuel economy that is improved over commercially available engines. The IPC engine concept applies principle attributes of the Diesel engine (unthrottled induction and high compression ratio), of ceramic adiabatic engine prototypes of the early 1980s (thermal insulation), of current HCCI engine prototypes (isochoric heat addition) and of Ernest E. Chatterton's "Simplic" 2-stroke engine prototype (isobaric heat rejection).

The thermodynamic sequence of both the Chatterton Simplic engine and the IPC engine, known as the Humphrey cycle, provides opportunity for high thermal efficiency, however it also carries the penalty of comparatively low volumetric efficiency, which adds the requirement that mechanical friction be commensurately managed (Figure 1).

Thermal Barrier Coatings (TBC): Thermal barrier coatings (TBC) provide the potential for higher thermal efficiencies of the engine, improved combustion and reduced emissions. In addition, ceramics show better wear characteristics than conventional materials. Lower heat rejection from combustion chamber through thermally insulated components causes an increase in available energy that would increase the in-cylinder work and the amount of energy carried by the exhaust gases, which could be also utilized [7]. A major breakthrough in diesel engine technology has been achieved by the pioneering work done by Kamo and Bryzik [8]. They used thermally insulating materials such as silicon nitride for insulting different surfaces of combustion chamber. An improvement of 7% in the performance was observed [9]. Sekar and Kamo [10] developed an adiabatic engine for passenger cars and reported an improvement in performance to the maximum extent of 12%. The experimental results of Morel *et al*. [11] indicated that the higher temperatures of the insulated engine cause reduction in the in-cylinder heat rejection, which is in accordance with the conventional knowledge of convective heat transfer. Woschni *et al*. [12] state that 5% of the input fuel energy cannot be accounted for which is of the order of the expected improvements. Havstad *et al.* [13] developed a semi-adiabatic diesel engine and reported an improvement ranging from 5 to 9% in ISFC, about 30% reduction in the in-cylinder heat rejection. Prasad and Samria [14] used thermally insulating material, namely partially stabilized zirconia (PSZ), on the piston crown face and reported a 19% reduction in heat loss through the piston.

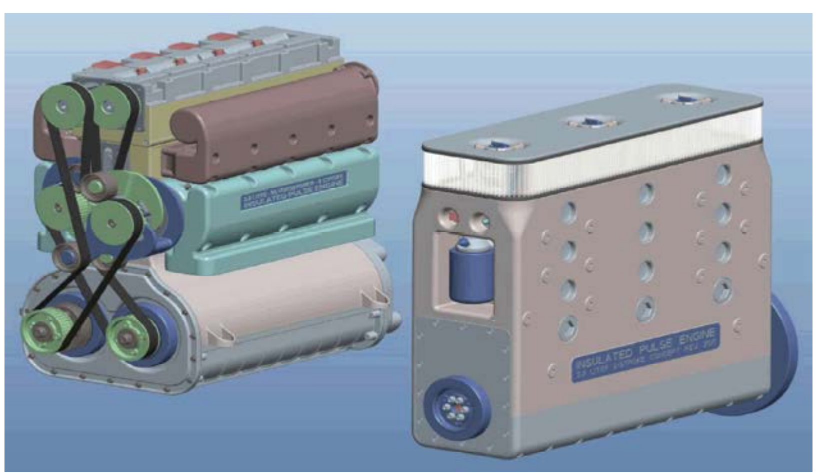

Fig 1: The Insulated Pulse Engine concept of 2010 (on left) is intended to function throughout a wide range of operating environments. The concept of 2011 (on right) is cost-reduced for use in more specialized environments [6].

Some Alternative Materials: Among possible alternative materials, one of the most promising is mullite. Mullite has low density, high thermal stability, stability in severe chemical environments, low thermal conductivity and favorable strength and creep behavior. It is a compound of SiO_2 and Al_2O_3 with composition $3Al_2O_3 . 2SiO_2$. Compared with Yttria-stabilized zirconia (YSZ), mullite has a much lower thermal expansion coefficient and higher thermal conductivity and is much more oxygen-resistant than YSZ.

For the applications such as diesel engines where the surface temperatures are lower than those encountered in gas turbines and where the temperature variations across the coating are large, mullite is an excellent alternative to zirconia as a TBC material. Engine tests performed with both materials show that the life of the mullite coating in the engine is significantly longer than that of zirconia [15]. Above 1273 K, the thermal cycling life of mullite coating is much shorter than that of YSZ [16]. Mullite coating crystallizes at 1023–1273 K, accompanied by a volume contraction, causing cracking and de-bonding. Mullite has excellent thermo-mechanical behavior; however its low thermal expansion coefficient creates a large mismatch with the substrate [17].

However, Bryzik *et al*. [18] mentioned a high output experimental single cylinder diesel engine that was fully coated and insulated with a ceramic slurry coated combustion chamber was tested at full load and full speed. The cylinder liner and cylinder head mere constructed of 410 Series stainless steel and the top half of the articulated piston and the cylinder head top deck plate were made of titanium. The cylinder liner, head plate and the piston crown were coated with ceramic slurry coating. An adiabaticity of 35 percent was predicted for the insulated engine. The top ring reversal area on the cylinder liner was oil cooled. In spite of the high boost pressure ratio of 4:1, the pressure charged air was not after cooled. No deterioration in engine volumetric efficiency was noted. At full load (260 psi BMEP) and 2600 rpm, the coolant heat rejection rate of 12 btu/hp.min was achieved. The original engine build had coolant heat rejection of 18.3 btu/hp-min and exhaust energy heat rejection of 42.3 btu/hp-min at full load. With the insulated build, the heat rejection of the coolant was 9.7 btu/hp-min and exhaust energy heat rejection was 54.1 btu/hp-min. The large increase in exhaust heat rejection at the expense of lower coolant heat rejection of the insulated engine indicates that some type of exhaust heat utilization device would be useful.

Comparison with Some Conventional Engines: Compared with naturally-aspirated 4-stroke Diesel engines at full throttle, a similarly displaced 2-stroke IPC engine at full throttle can consume only a twelfth of the fuel each combustion event. This is based on the observation that HCCI prototype engines consume 1/4 of the full throttle fuel that similarly displaced Diesel engines consume each combustion event and that only 1/3 of a piston stroke in the 2-stroke IPC engine applies to the compression cycle.

The 2-stroke IPC engine's compression cycle begins when the piston reaches 1/3 of a crankshaft stroke before TDC. The combustion chamber then transitions to become fuel-stratified when the piston reaches 1/8 of a stroke before TDC, whereupon fuel is direct-injected into a central region of the chamber. Fuel is constrained to and becomes mixed within, the central region using tumble-turbulence generated by inducted air surging inward from a fuel-devoid perimeter region of the chamber. Fuel stratification, in conjunction with spark ignition or other precision ignition method, permits throttling a locally-homogenous fuel-air equivalence ratio within the highly reactive range of 0.40-0.80 to assure a rapid, complete combustion reaction with practical torque band. A fuel-air equivalence ratio below 1.00 represents the deviation of a stoichiometric ratio toward fuel-lean.

Schouweiler [6] mentioned the combustion chambers passed through many changes it was observed similar in shape to the 2011 combustion chamber, the 4-stroke IPC engine of 2009 shows the combustion chamber at the transition position between stratified and unstratified, 12mm from TDC. The 4-stroke head assembly includes four small induction valves and four small exhaust valves within each cylinder. The valves are positioned such that fuel never contacts them and therefore pollution emissions cannot form within the crevices surrounding them. The 2-stroke IPC engine of 2010 employs the same head, with all eight poppet valves used for exhaustion. The central combustion chamber is now called the central region, the crevice chamber is now called the perimeter region and the annular passage is now called the transfer passage.

Combustion initiates centrally near TDC, propagates radially outward a short distance on a controlled supersonic wave front, whereupon the reaction efficiently concludes near TDC, assuring the entire fuel budget performs work on the piston through the full expansion cycle. Expansion is hyper-extended to 2/3 of the piston stroke, extracting all available combustion energy and eliminating the need for a cooling system. The chamber volume then develops a vacuum which draws fresh inducted air into the bottom 1/3 of the chamber. At BDC, induction ends and the piston begins quietly exhausting oxygen-rich combusted gasses residing in the upper 2/3 of the chamber.

Conventional emissions after treatment devices are not effective at scrubbing pollutants from the comparatively cool, pressure less exhaust gasses that the piston pushes out of the combustion chamber. The IPC engine must prevent the formation of pollutants by constraining fuel to a tumble-turbulent, thermally-insulated, crevice-free region of the combustion chamber specifically shaped (only at TDC) to support clean combustion. Rather than using brittle ceramic thermal insulators, as was the practice in the ceramic adiabatic engine experiments of the early 1980s, the IPC engine contains two thermally-insulating alloy steel disks, one integrally cast into the piston, the other into the cylinder head, to prevent the formation of quench-sourced pollutants. These thermally-insulating disks also promote rapid warm-up of the combustion chamber which minimizes cold-start forms of pollution emissions and they help retain combustion heat in the chamber to improve performance and fuel economy.

CONCLUSION

The heat rejection results from the insulated engine indicate the probable direction of the insulated engine program whereby high power densities and high efficiency are desired. A diesel engine operating near stoichiometry with the insulated engine with turbo compound device offers the most horsepower for a given engine displacement at the highest thermal efficiency. An insulated engine was demonstrated operating near stoichiometry (18:1) air-fuel ratio with normal smoke and fuel consumption. Calculation of the combined insulated and near stoichiometric engine with turbo-compounding showed the highest power density and best fuel consumption. Conversion of the high exhaust heat rejection and the minimized parasitic power for the low coolant heat rejection are the most likely contributing factors for the higher engine efficiency. Moreover, it was found that the LHR engine with 0.5 mm of mullite ($3Al_2O_3.2SiO_2$) insulation coating on piston crown, cylinder head and valves of diesel engine exhibits lower brake specific consumption than the conventional diesel engine. This insulation coating exhibits the brake specific consumption very close to conventional engine with deviation by about 1.76% higher at full engine load. This is due to effect of insulation; the heat free flow is restricted, which leads to reduction in heat transfer in case of LHR engine. The reduction in heat transfer leads to increase in combustion temperature, which leads to better combustion. The higher combustion temperature will lead to more expansion work. Also, LHR engine with 0.5 mm of mullite ($3Al_2O_3.2SiO_2$) insulation coating on piston crown, cylinder head and valves of diesel engine gives marginal rise in brake thermal efficiency when compared with conventional diesel engine. The brake thermal efficiency for LHR engine is higher by about 1.8 % than the conventional diesel engine at full engine load level. The insulation coating reduces the heat loss through combustion chamber resulting in increase in the charge temperature. This higher charge temperature leads to better combustion. However, this increased heat release is not converted into useful work in direct proportion but leaves with exhaust as seen from the rise in the exhaust temperature. It is observed that, the peak of gas pressure curve occurs 58.0 bars for conventional engine while for LHR (mullite coated) engine the peak of gas pressure curve occurs 58.88 bars. The increase in peak of gas pressure for LHR engine is due to elevated temperature of the insulated engine and better combustion of fuel. In addition, the LHR engines are exhibiting a higher rate of heat release compared with conventional engine. The reason for high rate of heat release is due to insulation, the higher heat detainment inside the combustion chamber is exhibited. This leads to evaporate the fuel at faster rate, which helps possibly to better premixing, reduced diffused combustion. Further, it results in complete combustion of fuel. Hence, it releases more amount of heat [19].

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