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Advanced modern low emission two-stroke cycle engines

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Abstract: This paper reviews recent engines and associated technology offering potential low emission two stroke cycle operation for a range of applications. The study considers and discusses successfully applied modern production engines together with concepts exploring advanced possibilities for future application. Published results from research and development projects and data from available technology are compared in terms of specific performance. The paper does not compare combustion strategies or fluid dynamic aspects of two-stroke cycle engines, but does consider and compare data from engines using crankcase, external and stepped piston scavenging intended for automotive, marine and defence applications.

Keywords: Two stroke cycle engine, stepped piston engine, step piston, external scavenging engines, variable compression ratio, hybrid electric vehicle, direct injection, downsizing, low emissions.

I. INTRODUCTION

The two stroke cycle engine has experienced significant challenges to its existence as ever more stringent emissions regulatory standards are introduced. Indeed many historical manufacturers of such engines have replaced two stroke engines within their product range with four stroke cycle replacements, accepting the reduced performance that is evident from such a move whilst meeting the key goal of emission legislation. The dilemma that exists is that the two stroke cycle engine has the potential to achieve competitive low emission characteristics [1][2], if it could overcome serious inherent durability problems. Operating a two stroke engine with direct fuel injection increases the thermal loading on the engine. Furthermore early carburettor fuel systems delivered excess fuel that often achieved a cooling effect preventing subsequent piston durability problems. The introduction of advanced direct fuel injection systems eliminated this cooling effect and readily demonstrated results of improved thermal efficiency. If roller bearings are employed within a crankcase scavenged engine then total loss lubrication is inevitable, due to the passage of lubricant from the bearings to the combustion chamber via the transfer ports. Some methods of recirculation of excess oil have been demonstrated [3], however to achieve low emissions this oil supply must be maintained at a very low level in comparison with early two stroke engine examples. A number of engine developments have been proposed to achieve low overall emission characteristics and this paper will discuss these developments together with an analysis of specific performance data from published papers. Engines using a range of cylinder charging methods are considered including uni-flow, cross and loop scavenging. Uni-flow scavenging where flow is uni-directional from intake ports or valves at one end of the cylinder to valves at the other end normally offers the highest charging and scavenging efficiency. If minimum engine unit size is a key objective cross scavenging offers a minimum cylinder centre distance since the cylinder inlet or transfer ports are arranged directly opposite the exhaust ports disallowing any space for ports at the side elevations of the cylinder. This necessitates a deflector on the piston crown to redirect the incoming charge up into the combustion chamber. If inlet ports can be arranged angularly around the periphery of the cylinder, directed away from the exhaust port, then loop scavenging can be achieved where the incoming charge trajectory forms a loop path as it scavenges the exhaust gas from the cylinder.

II SPARK IGNITION TWO STROKE ENGINES

2.1 CRANKCASE SCAVENGED ENGINES

Schlunke [2] in 1989 and Smith et al [4] in 1993 presented details and developments of the Orbital Combustion Process (OCP), an injection system where high pressure air (5.5 bar) and fuel (6.2 bar) are injected directly into the combustion chamber of the two stroke cycle engine. Developed by the Orbital Engine Corporation of Australia, the system was originally applied to an unusual rotary engine that Orbital were developing. The system uses a fuel injector for fuel metering and with the addition of solenoid controlled high pressure compressed air a highly atomised fuel-air mixture is propelled directly into the combustion chamber. On realising the potential application of the fuel system to two stroke engines Orbital gained significant interest from major automotive manufacturers including Ford[5][6], Jaguar[6], FIAT, General Motors[6], Piaggio and Bajaj in India. Significant examples of published work exists [6-10] presenting results using an Orbital inline three cylinder 1197cm3 engine. Automotive manufacturers were particularly interested in the two stroke engine's very low emission characteristics, high specific performance and flat torque output. Indeed results were so promising that interested collaborators paid significant initial and subsequent license fees in order to assess the technology. The crankcase scavenged OCP1200 engine despite demonstrating very low emissions and high efficiency suffered from poor durability characteristics and was therefore largely abandoned by the car manufacturers. However in 1995 the work of Eisenhauer [11] demonstrated improved durability and in 2000 Shawcross et al [12] published results of extensive durability testing via fleet vehicle trials in Australia. Successful production application of Orbital systems was achieved in conjunction with Siemens on engines such as the Aprilia DITECH 50cm3 motorcycle scooter as published by Ambler and Zocchi [13] and Archer and Bell [14] and the Mercury Marine Optimax outboard motor range. The Aprilia DITECH system is largely a development of the Orbital SEFIS (Small Engine Fuel Injection System) as published by Leighton et al [15]. Peugeot Motorcycles and Kymco introduced two stroke direct injection scooters in 2002 and 2004 respectively. The design, development and production of a low cost direct injection system presents significant challenges. On small capacity engines the direct injection (DI) system application can substantially increase engine unit cost making production viability questionable. In order to address high emission levels of current two stroke engines, significant interests for direct injection systems have been shown in India for application to two and four stroke motorcycles [16-18]. Bajaj launched the first gasoline direct injection two stroke engine rickshaw in 2007 [19]. Two stroke engine developments were published by Duret et al [20][21] of the Institut Francais du Petrole (IFP) in 1992/3 in response to growing interest in two stroke engine solutions for modern low emission automotive applications. These developments used the novel principle known as IAPAC (Injection Assiste Par Air Comprime) of applying a surge tank attached to the crankcase via a reed non return valve [22]. The surge tank feeds low pressure air from the crankcase to a cam actuated poppet valve in the cylinder head. A conventional low pressure fuel injector is positioned just behind the poppet valve. On actuation of the poppet valve a highly atomised air fuel mixture is passed into the combustion chamber. Similar to the work of Schlunke, significant research has been published by Duret et al (1992, 1993) based upon an inline three cylinder configuration of 1230cm3 swept volume. The concept was explored in 1993 in collaboration with automotive companies such as Peugeot [1][20], FIAT [21] and joint Peugeot Citroen (PSA) and Renault collaboration [23-26]. In a similar approach to the Orbital SEFIS system a low cost version of IAPAC entitled SCIP (Simplified Camless IAPAC) which was developed in 1999 for low cost motorcycle scooter applications [29] and outboard manufacturers such as Selva. Amongst others, Italian manufacturer Piaggio collaborated with IFP [30] on application development of the SCIP system. Through the extensive research and development of Nuti et al [29-31] several notable systems for the development of new low emission two stroke engines for motorcycle scooter application were published from 1988 to 1998. Perhaps most notable is the Piaggio FAST (Fully Atomised Stratified Turbulence) system. This uses direct injection via a crank driven piston pump situated on top of the cylinder head. Fuel is fed to the pump in proportion to the air mass flow rate entering the crankcase. The piston pump which has a diameter much smaller than the power cylinder is used to inject the fuel mixed with air directly into the combustion chamber. A single fluid direct injection system developed originally by Ficht [32] of Germany was published in 1993 and found commercial application with Outboard Marine Corporation (OMC), USA. The fuel system injects gasoline only using a magnetically actuated hydraulic ram system. Fuel is injected at high pressure (approx 30 bar) directly into the combustion chamber. In 2003 outboard manufacturer Evinrude released the first of a range of E-TEC direct injected two stroke engines which is based on Ficht technology as described by Strauss et al [33]. Queen's University of Belfast have long been active in the field of two stroke engine research and have presented much data in 1994 using a cross scavenged engine [6] of 270cm3 swept volume. Results with air blast direct injection with this crankcase scavenged engine has been presented by Blair et al.

III COMPRESSION IGNITION TWO STROKE ENGINES

3.1 CRANKCASE SCAVENGED ENGINES

Automotive two stroke diesel engines have also been developed in response to the significant potential for car application. The work of Matsuda et al [7][53] of Yamaha Motor Co published research data for a semi direct injection two stroke diesel engine. The engine was claimed to achieve low emission levels close to Euro 4 [54]. The engine forming the subject of research was a 982cm3 twin cylinder design. Good results were observed following installation in a small Japanese Kei-class car replacing the standard 660cm3 four stroke engine. Power of 33kW at 4000 RPM is claimed with maximum torque of 80Nm at 2500 RPM. The engine requires computer control of oil supply to further reduce consumption. A key feature of the engine is the use of an exhaust port control valve allowing the advancement of port timing at higher engine speeds whilst offering the ability to close the valve thereby retarding the exhaust port timing for low speed operation. Furthermore for the two stroke engine designer the most relevant compression ratio value is that derived by the charge trapped after exhaust port closure. Variation of exhaust port timing therefore allows variation of the trapped compression ratio. This allows higher than design compromised ratios to be available at part load conditions whilst lower compression ratios can be employed at full load operation, thereby improving the overall efficiency of the engine particularly at part load conditions. Matsuda et al claimed a compression ratio variation from 13:1 to 18:1 was achievable with their system. To improve noise vibration and harshness (NVH) of the twin cylinder layout a balance shaft was incorporated into the lower section of the crankcase. The main challenge is achieving acceptable long term durability with this crankcase scavenged engine. Using the crankcase for supply of inlet air and the conflicting need to therefore severely limit the supply of lubricant (since it can contaminate the scavenge air supply) has been shown to result in poor durability.

3.2 EXTERNALLY SCAVENGED ENGINES

In a similar approach to their gasoline spark ignition engine research, the compression ignition version of the Toyota S-2 was also scavenged with a Roots type supercharger using poppet type intake and exhaust valves. Results have been presented by Nomura and Nakamura [37] with pre chamber indirect injection. Some significant advantages were claimed for the S-2 diesel and gasoline engines over comparable four stroke engines especially in terms of reduced NOx and particulate emission, start ability and NVH. However fuel economy improvements were highlighted as requirements for future adoption of the engines. Research published by Knoll et al [9][55][56] has shown results achieved with an inline 3 cylinder two stroke diesel automotive engine using blower charging developed by AVL List GmbH of Graz, Austria. The engine uses uni-flow scavenging which is known to offer higher scavenging and trapping efficiencies [57][58] than can be achieved with cross or loop scavenging, however there are penalties in terms of overall engine size, mass and cost. This would normally limit the application of uni-flow scavenging to relatively large passenger car applications. At the 1999 Frankfurt Motor Show [59] Daihatsu displayed their E202 two stroke engine under development to achieve the key goal of 3litres per 100km vehicle fuel consumption in a Sirion 2CD. The engine was a 1 litre 3 cylinder unit using external supercharger scavenging with variable nozzle turbocharger and intercooler. Little is known regarding the performance characteristics of the E202 engine due to minimal published material.

IV. HOMOGENOUS CHARGE COMPRESSION IGNITION (HCCI) / CONTROLLED AUTO IGNITION (CAI) TWO STROKE ENGINES

Following the early work of Onishi et al [60] of the Nippon Clean Engine Research Institute where the effects of Active Thermo-Atmosphere Combustion (ATAC) was explored using crankcase scavenged two stroke cycle engines, much further work has been undertaken. This has resulted in considerable research effort focussing on the ability of two and four stroke engines to operate in conditions of auto ignition. Promising results have been reported in terms of emissions and specific fuel consumption reduction. Initially results demonstrated very low hydrocarbon emission by operation using this form of combustion however more recently its adoption to counter NOx emission has become a major research focus. Due to the inherent internal exhaust gas recirculation available with two stroke cycle engines it has been argued by Turner [61] that control of auto ignition is easier to achieve in a two stroke cycle engine. Honda achieved notable application success with their EXP-2 440cm3 single cylinder motorcycle through research and development of the Active Radical Combustion (ARC) system and explored further analysis of stabilising AR combustion using smaller capacity engines through the research of Ishibashi et al [62][63]. Duret et al of IFP have also published work [64][65] using the crankcase scavenged IFP IAPAC engine operating in ATAC or auto ignition modes and the marked improvements observed in terms of emissions and fuel consumption. Recent research work based at Ricardo originally using the earlier "Flagship" concept engine [36][66] has also been explored further for HCCI operation of two stroke and four stroke engines. Under the support of a Foresight Vehicle programme Ricardo are currently developing a research engine that can switch between two stroke and four stroke cycle operation in order to achieve significant fuel consumption reduction. The engine uses electro-hydraulic poppet valve actuation together with an advanced control system that is able to automatically switch between two stroke and four stroke operating modes.

V.CONCLUSIONS

A range of advanced two stroke engines offering low emission potential for future commercial application have been compared in terms of their technological developments and unique features. An analysis where published data has been available has provided an interesting comparison of each different approach to meet future two stroke cycle engine design objectives. Whilst the two stroke engine offers high power density and low cost advantages, greater complexity and hence increased unit cost is inevitable in order to meet ever more stringent emission standards. By application of direct injection systems, high speed poppet valve actuation, active EGR control to enable a wide range of HCCI operation and variable compression technology the two stroke engine still has potential to provide competitive low emission powertrain solutions. Direct injection is now a requirement for any modern automotive two stroke engine. The relative ease of application of variable compression ratio operation to the two stroke engine should not be overlooked and offers interesting prospects for future research and development. Further development of engines such as the Ricardo "2/4 Sight" and Lotus "OMNIVORE" therefore hold strong potential, however in order to address the challenge to minimise unit cost the stepped piston engine offers strong future prospects. Each of these engine types can present strong solutions for future engine downsizing.

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