Conventional Fuel Injection System in Two-Stroke Engines

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Abstract

Carburetted 2-stroke engines are a worldwide pandemic. There are over 50 million 2-stroke cycle engines in Asia alone, powering motorbikes, mopeds, "three-wheelers", "auto-rickshaws", "tuk-tuks", and "tricycles". These carbureted 2-stroke engines are characterized by high levels of hydrocarbon (HC), carbon monoxide (CO), and particulate matter (PM) emissions. Direct injection is a technology that has shown a great ability to reduce these emissions while at the same time improve fuel economy. A prototype kit has been designed for use in retrofitting existing carbureted two-stroke engines to direct injection. The kit was designed for use on a TVS 50; a motorcycle from the INDIA that is commonly used as a transportation. It is however, a relatively common engine design and TVS manufactures similar models for sale all over the world. The conventional fuel injection system kit incorporates the Orbital air blast direct injection system. This injection system has been implemented in TVS 50. The design involved replacing the existing cylinder head with one designed to incorporate the direct injection valves as well as a modified combustion chamber. An external compressor was added to supply compressed air to the system. The carburettor was refined with a throttle body outfitted with a position indicator, and an encoder system was added to provide speed and position feedback to the engine control unit (ECU). Once design and manufacture of the system was complete, it was installed on the motorcycle. The motorcycle was then mounted in a low inertia eddy current dynamometer test cell for calibration. Calibration was done on the dynamometer for power and engine performance. The system was also tuned in real world road tests for drivability. When calibrations were complete emissions and fuel consumption measurements were taken for the vehicle. The results showed an 88% reduction in hydrocarbon emissions and a 72% reduction in carbon monoxide emissions versus the baseline engine, while at the same time virtually eliminating visible smoke. The CFI system also showed a 32% increase in fuel economy, and had similar to better performance than the carbureted engine. The CFI system also showed improved cranking and idling characteristics over the carbureted engine.

Keywords: Direct Injection, Two-Stroke, Air Pollution.

1. INTRODUCTION

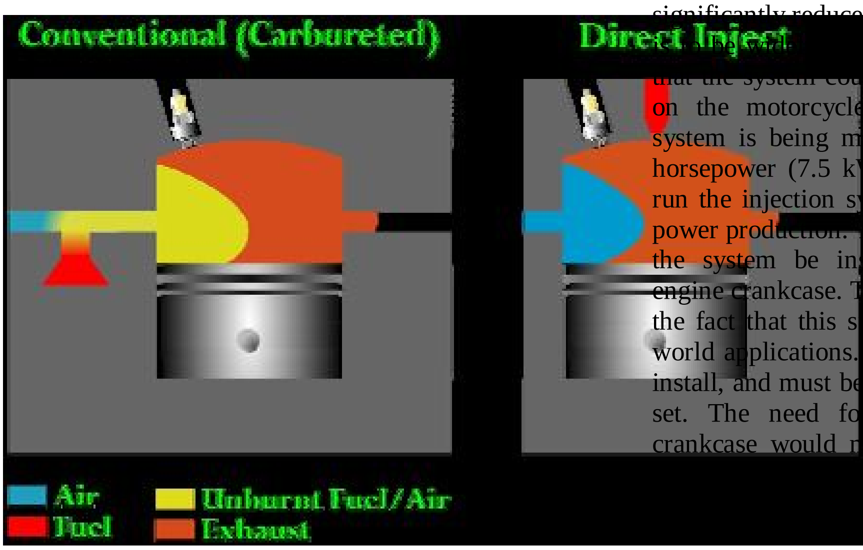
Air pollution is on the increase in many Asian cities due to the widespread use of carbureted two-stroke cycle engines. These engines are typically used as the power source for "two-wheelers". 1). Their rugged yet simple construction, and 2.) their low cost and 3.) Their high power-to-weight ratio. Unfortunately, two-stroke cycle engines are also characterized by high levels of unburned hydrocarbons, carbon monoxide, and particulate emissions. The high hydrocarbon emissions from carburetted. Two-stroke engines result from the scavenging process used. Scavenging refers to the process by which the burned exhaust gasses are flushed from the engine. In a conventional "carburetted" two-stroke engine the fuel is entrained in the intake air stream before the combustion air enters the crankcase. The charge is compressed in the crankcase by the underside of the piston, and enters the cylinder when the piston uncovers the transfer ports. Combustion products from the previous cycle are forced or "scavenged" from the cylinder with this new air fuel charge. Unfortunately, the exhaust ports are also open at this time, allowing 30%-40% of the fuel to be lost directly into the exhaust stream.

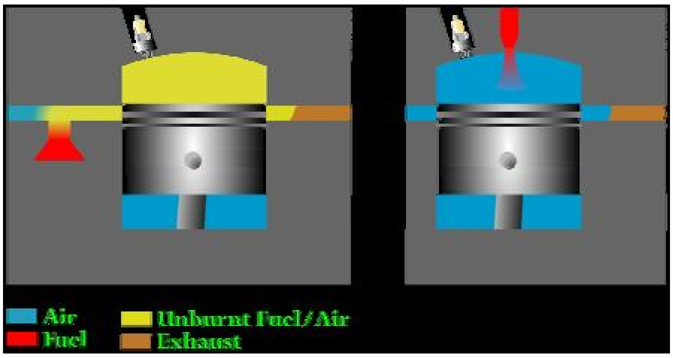
1. At idle conditions the losses can be as high as 70%.
2. The high carbon monoxide emissions result from rich air to fuel ratio typically seen in these engines. High residual gas fractions within the cylinder lead to an environment in which consistent ignition is difficult. In order to improve combustion stability rich air fuel mixtures are typically used. This excess of fuel leads to incomplete combustion and high carbon monoxide levels.

3. Finally, the high particulate emissions result from the unstable combustion, excessive lubrication (typical in small two stroke engines), and a lubrication system which allows lubricating oil to be dissolved in the fuel.
4. In a typical 2-stroke, the oil mixes with the fuel at the carburettor. As the air/fuel/oil mixture transfers into the crankcase, the fuel dissolves the oil. This action reduces the amount of oil deposited on the cylinder wall (or other critical components) as it is essentially ‘washed’ out of the engine by the fuel.

1.2 CONVENTIONAL FUEL INJECTION SYSTEM

The conventional fuel injection system is a technology that has shown the ability to greatly reduce emissions from two-stroke engines. In a CFI system the carburettor is refined, and the fuel is introduced into the combustion chamber via an injector mounted in the top of the chamber’s cylinder head. This allows exhaust products to be scavenged from the cylinder using air only. Fuel is injected into the cylinder later in the cycle, greatly reducing the amount of unburned fuel that is allowed to escape during scavenging. The CFI process allows for a locally rich region around the spark plug, eliminating the need for enrichment of the entire cylinder to achieve stable combustion. Elimination of rich air/fuel ratios significantly reduces carbon monoxide emissions





2. SYSTEM DESIGN

2.1 DESIGN STRATEGY

In approaching the problem of modifying existing two stroke engines for operation using conventional fuel injection, several key constraints were used to evaluate potential direct injection systems. The first constraint was that the base technology needed to be commercially available. While designing a direct injection system specifically for applications has potential advantages, the design time needed to bring a system to maturity does not fit within the constraints of this project. The second constraint employed was that the final system could not greatly reduce the ability of the two-stroke engine to operate in adverse conditions. While any modification made to something as simple a carburetted two-stroke engine makes it inherently more complex, this complexity could not significantly reduce the reliability of the engine if it ...epted. The third constraint was that the system could not have a large power draw on the motorcycle. The vehicles to which the system is being modified only produce about 10 horsepower (7.5 kW). Any large power draw to run the injection system is not feasible given that power production. The last main constraint was that the system be installed without machining the engine crankcase. This is a crucial constraint due to the fact that this system is targeted at developing world applications. The kit must be inexpensive to install, and must be installed with only a basic tool set. The need for complex machining of the crankcase would make the installation of the kit ...leveloping countries. Paramount ...r design constraints was that of ...ons reduction. Significantly reducing emissions from existing two-stroke engines is the main reason for the project. Therefore setting emission reduction goals was necessary. Based on research of available CFI technologies, a 50% reduction in carbon monoxide, and a 70% reduction in unburned hydrocarbons was set as the target reduction, and although no equipment was present to quantify particulate matter reductions, minimization of visible smoke was also set as a goal

2.2 CHOICE OF SYSTEM

Two commercial direct injection systems were investigated for use in retrofit applications: Fichte and Orbital. The Fichte system, now owned by Bombardier, utilizes a hammer injection system. Fuel is introduced into the injector at low pressure, and a solenoid is used to "hammer" the fuel, rapidly increasing its pressure and using that pressure to inject and atomize the fuel. This system has the advantage of having relatively few parts, which makes it attractive as a solution. Unfortunately the solenoid used to hammer the fuel has a high power/voltage requirement (between 38 and 43 volts) and therefore is not suitable for retrofit to small low power engines. The Orbital system relies on an air-assisted, "spray guided" injection system known as the Orbital Combustion Process (OCP). The OCP system utilizes a gasoline injector to meter the fuel. Compressed air is then used to atomize the fuel into tiny droplets. The size of the droplets is key due to the short time available for vaporization. Of the available commercial systems the OCP system boasts the smallest droplets with a Sauter Mean Diameter (SMD) of 7 micrometers. The advantages of this system are the low power draw as well as its proven commercial viability. The durability of the Orbital OCP system has been demonstrated by endurance tests and by the successful conclusion of a large fleet trial. In this trial, 100 Ford Festiva vehicles were equipped with two-stroke Orbital engines. These vehicles successfully accumulated over five million kilometres of operation while showing excellent reliability and durability. The Orbital OCP system has also shown real world reliability and has now been in use for over six years on Mercury Optimax outboards and for over four years in Sea Doo watercraft equipped with Bombardier engines. The Only disadvantage seen with the Orbital system is the added complexity of providing compressed air to the system. When the two systems were compared with the constraints of the project, the Orbital system was chosen. The added complexity of adding an air compressor to the system was a detriment, however it was still considered preferable when compared to the large power draw of the Fichte system. The Orbital system also has a proven track record and is at full commercial maturity.

2.3 KEY COMPONENTS

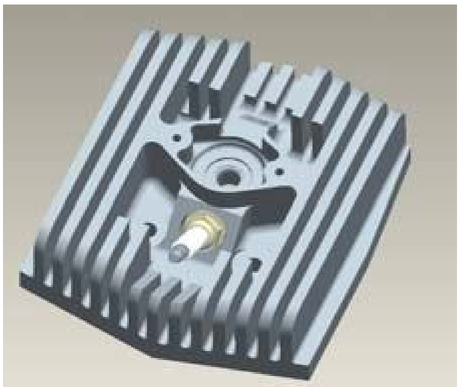
There are several components that are key to modifying the Orbital direct injection system. The most visible component is the cylinder head. The stock cylinder head needs to be replaced in order to facilitate the mounting of the CFI injection valves as well as incorporating a modified combustion chamber. Since the Orbital system employs an air injector to atomize the fuel, there is a need for a compressed air source. This need is met by the use of a small belt driven piston compressor with carburettor and i a throttle body. The throttle body is equipped with a position indicator to serve as one of the primary load indicators for control of the injection system. An encoder system provides a speed reference for the system as well as providing phasing control, for the injection and ignition events. A low cost engine control unit is added to facilitate injection and Ignition control. A high pressure, low flow, low current draw, fuel pump is added to provide the proper fuel pressure to the system, and finally, a solenoid oil pump is also added to allow precise metering of lubricating oil to the system.

2.3.1 Cylinder Head

Once the Orbital system had been identified as the best system available for modifying applications, design work began on the CFI kit. The cylinder head was the first major component design approached. A solid model was created of the cylinder head, and it was CNC machined out of 7075 aluminium. In production this component would be cast, and a limited amount of finish machining would be done, however, since this was the prototype unit and only one head was needed, casting was not economically feasible. Although the design of the head is complex, its design is not markedly different from that of an OEM Orbital direct injection system; therefore it will not be discussed in great detail here. For a discussion of the base Orbital system see the Figure 2: Alpha Cylinder Head CAD Model and CNC Machined Prototype

2.3.2 Air Compressor

With the head design complete, work began on a way to successfully provide compressed air to the system. The Orbital system generally uses a small cam driven piston compressor. This compressor rides on an eccentric lobe machined onto the crankshaft. This is not a viable option for retrofit due to the fact that it would require extensive machining of the crankcase. This violates one of the main design constraints and is also unfeasible given the cost increase that it would represent. These left two main options: either design a completely new air compressor system, or find a way to incorporate the cam driven design into the system.



Due to the extensive time and effort needed to validate a new design, the cam driven pump was chosen as the best solution for the prototype kit. The only access to the crankshaft available on this motorcycle is at the magneto. The magneto/stator is housed in a cast aluminium case. This was chosen as the location for installation of the air compressor. A balanced eccentric cam was designed to mount to the magneto and provide the driving force for the compressor. The idea of mounting the compressor to the cast aluminium case was put forth, but after initial inspection it was determined that the case alone was not rigid enough to support the cyclic loading that would be seen due to the compressor. The case needed to be strengthened, so a steel ring was manufactured to precisely meet the contours of the housing. A boss was welded to the ring for the air compressor to mount in, and the entire ring was epoxied into the cast aluminium case. Finally finish machining was done to the boss after installation into the case to ensure the correct stroke for the air pump. In mass production, the thin case used could have been replaced by a new sturdier cast aluminum case eliminating the need for the steel ring. However, casting of the low number of components needed for a prototype is cost prohibitive. Upper Left - Stock cast aluminum case Upper Right - Machined ring with welded boss Middle Left - Ring epoxied into cast aluminum case Middle Right - Finish machining of case Lower Left - Modified case mounted to engine Lower Right - Air compressor follower riding on cam This design worked well for much of the early testing, but as dyno calibration proceeded, and the compressor saw constant operation at high speed, lack of lubrication became an issue, and the compressor failed. This situation was easily remedied for the remainder of calibration and testing by periodically lubricating the compressor and disassembling it for visible component inspection. While this approach worked well for the completion of calibration and testing, it is not viable for a commercial application, as it would add maintenance requirements and would undoubtedly reduce the overall reliability of the system. Due to these reasons a new oiled enclosed pump has being designed. This design leverages many of the components from the existing cam driven compressor to reduce design validation time.

2.3.3 Charging System

The stock charging system of the Kawasaki is a 6 volt system. The Orbital system however, requires 12 volts, so a modification had to be made. Two main options were considered: the first was using a DC-to-DC converter, to provide a 12-volt supply for the Orbital system. This option was rejected due to the inefficiencies in inexpensive DC-to-DC converters, as well as the low power levels provided by the base six-volt system. The other option was converting the motorcycle to a 12-volt system. This is a slightly more difficult proposition, due to the need to replace all of the electrical components on the motorcycle to facilitate it. However none of the components are expensive, so converting the system to 12 volts was chosen as the preferred method. In this case the stator and magneto were completely replaced. However the stock stator was rewound, and could provide the necessary voltage and current needed to support the system. The reason for replacement was that the new magneto came from a system that was already equipped with Orbital direct injection, and therefore was already equipped with the encoder system needed.

2.3.4 Encoder System

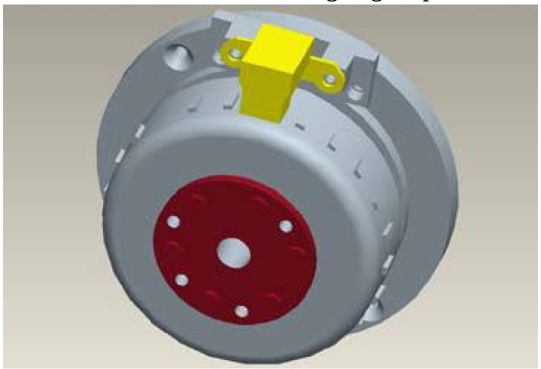
The Orbital system requires a “24 minus 1” tooth count for use in speed and phasing control. This means that a magnetic pickup is mounted over a target wheel that has 23 teeth and a space where the 24th tooth would be is left empty. This missing tooth serves as a reset for the system, telling it that a Complete revolution has taken place. The remaining 23 teeth allow for phasing control to ensure that the injection and ignition events occur at the desired timings. As discussed earlier, the magneto used in converting the system from 6 to 12 volts already was equipped with the 24 minus 1 pattern, and therefore, the only real modifications needed to facilitate the mounting of the encoder system were a modified mounting plate for the stator and a mounting plate for the magnetic pickup.

2.3.5 Throttle Body

Since the carburettor is needed to admit air to the system, it was refined with a simple throttle body. This throttle body is equipped with a throttle position sensor (TPS) and serves as one of the primary load indicators, along with engine speed to determine the amount of fuel that is needed. For the prototype model the throttle body had a near press fit into the intake pipe of the engine, so that tolerance fit was used to secure it. However, when the mounting technique was tried with other throttle bodies and other engines, manufacturing tolerance came into play, with some not fitting at all and some being to loose to provide mounting strength. For production kits the throttle body will be mounted using a simple bracket, and a flexible coupling.

2.3.6 Fuel/Oil Pump

The stock carburetted system uses gravity feed to supply fuel to the carburettor. This is obviously not sufficient to provide pressure for an injection system. Therefore a small piston style electric fuel pump is added in order to provide pressurized fuel to the injector rail. Since an ECU is already needed to control the injection system, a solenoid style oil injection pump can also be added. The ECU controls the oil pump and meters in oil proportional to the amount of fuel. This ratio is tuneable within the ECU, and allows for higher oiling rates during high speed and high load operation, while at the same time allowing for greatly reduced oiling rates at low speed and low load points. This ability to tune oil admission further reduces the particulate matter emissions while at the same time ensuring engine protection.



3. CALIBRATION AND TESTING

One of advantages gained from implementation of direct injection is the ability to tune the system at many speed-load points. Fuel metering, injection timings and durations are all tuneable parameters as well as ignition timings. The Orbital system uses map based calibration with throttle position engine speed and amount of fuel injected as ordinates. In order to calibrate the system it is necessary to hold some of these ordinates constant while varying others. This is almost impossible to do during road testing, so a dynamometer test cell was used to allow for engine speed and load control. A SAJ low inertia eddy-current dynamometer was selected due its appropriate power range, as well as the low inertia it provided. Low inertia is important in testing single cylinder engines due to the fact that the crankshaft speed is not uniform. The acceleration of the crankshaft changes direction twice per cycle and if the dyno's inertia is too high this can lead to engine failure with the end of the crankshaft frequently breaking off due to fatigue. To further minimize the risk of failure the dyno was not coupled directly to the crankshaft, but instead coupled to the output shaft of the transmission. This allowed the transmission to take up some of the acceleration changes, and minimize the strain on the crankshaft. There are some losses in the transmission, and therefore the power measured by the dyno is not actual engine power. However, since this is a retrofit project, comparison with the baseline carbureted engine is more important than actual engine power and since both the carburetted and retrofitted engines were tested with the same procedure, comparisons using incremental gains or losses are valid. Once the dynamometer was set up, calibration of the system began. The system is very tuneable; power, emissions and durability can all be greatly affected by the injection timings and durations that are used. For this calibration, minimizing emissions while maintaining roughly equivalent power levels to the carbureted system was chosen to be the goal. Much of the calibration process is proprietary and will not be discussed here; however, the basic approach used involved calibrating on a point by point basis, and then smoothing the maps to allow for stable operation, both at steady state and during transients. Following dyno calibration, further road calibration was done to ensure good drivability and reliability in conditions that are not easily duplicated on a dyno.

4. RESULTS

Once the calibration process was completed, emissions and fuel consumption measurements were made on both the carbureted and conventional fuel injected engines using a modified steady state "Indian Drive Cycle". Emissions measurements were made using a Vetronix PXA-110 emissions analyzer. The results of this testing are summarized below in Table 1.

Table 1.Fuel Consumption and Emissions Summary

ENVIROKIT™ VS. CARBURETTED BASELINE			
	Carburettor Baseline	**Conventional Fuel Injection**	**% Improvement**
Fuel Economy (km/lit)	31	41	32%
DISTANCE NORMALIZED EMISSIONS (GM/KM)			
Unburned HC's (C6H14)	4.4	0.6	88%
Carbon Monoxide (CO)	1.3	0.4	72%

As can be seen from the table the emissions reduction goals were more than met. The system showed a showed a large decrease in emissions while at the same time increasing fuel economy. The power requirements were also met, with the system showing an approximate 0.25 bhp increase in peak power.

5. CONCLUSION

A direct injection retrofit kit has been designed to prove the validity of retrofitting the estimated 50 million two-stroke engines in Southeast Asia. The system is based the Orbital direct injection system. The kit consists of new cylinder head, fuel and air injectors a piston style air compressor to provide compressed air for the air blast system, a throttle body to replace the carburettor, fuel and oil pumps and an engine control unit. The system was modified to a TVS50 motorcycle. After design and fabrication of the components the system was assembled and calibrated on a dynamometer. Emissions reductions were considered key during the calibration of the system, but performance could not be compromised. Following calibration, the modified system was tested. Compared to the carburetted system, the modified system displayed an 88% reduction in unburned hydrocarbon emissions and a 72% reduction in carbon monoxide emissions while at the same time virtually eliminating visible smoke from the exhaust. Due to the near elimination of short circuiting losses as well as more complete combustion, the retrofit system also showed a 32% increase in fuel economy. The system designed was a prototype, and further engineering needs to be completed in order to bring the system to Commercial maturity. Due to the remarkable emissions reductions possible though implementation of this system it is believed that it could have a vast impact in reducing emissions from two-stroke engines in the developing world, improving ambient air quality and improving the way of life for millions of people.