RADICAL COMBUSTION: NEW CONCEPT FOR TWO STROKE ENGINES

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ABSTRACT

Radical combustion is a process initiated by the radicals, which behave as local energy spots. These radicals are generated from the previous combustion cycle and recycled to the next combustion cycle. As exhaust emission discharge in two-stroke engine affected significantly by the scavenging processes, hence radical combustion mostly associated with combustion process of the two-stroke engine. In the present study a two-stroke SI engine was modified in order to achieve radical combustion process. A new exhaust throttling system was designed and used for this purpose. Engine power, fuels consumption, and exhaust emissions were the parameters studied. The effect of the radical combustion process on these parameters was studied at different engine running conditions. Significant improvements in fuel consumption exhaust emission levels in particular NO_x , and exhaust temperature were achieved when the engine was running on radical combustion.

During radical combustion, the exhaust port throttling has been tested at a range of 2 to 16mm (exhaust port reduction area is 1 – 8%). A comparison of the engine performances while running on radical combustion is carried out.

1. INTRODUCTION

Stringent legislation concerning the pollution of atmosphere by engine exhaust gases have been tightened recently and hence placed an extensive pressure on engine manufacturers to meet these emission standards. Two-stroke S.I. engines are known for their high emission levels in particular unburned hydrocarbon UHC and NO_x ¹. Different research and development programs are initiated in order to eliminate these fundamental weaknesses of two-stroke engine². Hence a number of techniques have been studied and used to improve fuel economy and emission levels of the two-stroke S.I. engines. Most recently, the use of radical combustion process in two-stroke engines has been reported as a promising way to achieve these improvements³.

The hot residual gases excessively present in two-stroke engines seems to have a major role on the onset of abnormal combustion especially at light loads where there is excessive cyclic variation and irregular combustion⁴. The variation of residual gas distribution at the vicinity of the spark plug due to improper local scavenging is the main factor that affects the initial period of combustion. It is reported that the divergent effect of the residual

gases on the abnormal and knocking combustion and the irregular combustion and misfiring are the most important aspects of combustion process in two-stroke engines^{4, 5, 6}. These effects are due to auto-ignition of fresh charge and the dilute of the fresh charge and inhibit the flame propagation which in turn leads to higher HC emissions and poor fuel economy.

The two-stroke engine combustion process is closely associated with the scavenging flow characteristics and the quality of residuals present in the cylinder. Several studies^{7,8,9} indicate that cyclic variation and irregular combustion are closely related to the scavenging process. Modification in the scavenging passage and other scavenging flow related systems could reduce irregular combustion. It was revealed that the cyclic variation and irregular combustion are caused by factors that affect the initial period of flame development caused due to local factors at the ignition site. Besides a variation in the scavenging, flow pattern can lead to variations in the quantity of the residuals remaining in the cylinder.

It is reported that developments of existing engines for exhaust and intake tuning, improved carburation and scavenging flow organization, optimization of engine operating parameters could improve particular operating conditions however, the overall loss of fresh charge remains inevitably between 15 – 35%. The use of fuel injection systems has been reported to substantially improve conventional engines¹⁰. Some other alternative developments have been proposed. These included intake system development, the use of dual-intake systems. However, the emission levels and the fuel consumption have impeded all the above developments. High temperatures seem to influence the NO_x levels while scavenging process influences the UHC (unburned hydrocarbon) levels.

A new combustion process initiated by the generated radicals from the previous combustion cycle could be of potential influence on the emission levels and fuel consumption of two-stroke engines. These radicals are used as local energy spots during the mixing process with the fresh charge. The establishment of such combustion process required a certain running conditions. These conditions included the amount of the residual gases to be trapped each cycle, the mixing process of the fresh air-fuel charge and the residual gases to form a stratified mixture, the combustion chamber and piston geometry, the air-fuel ratio, the compression ratio, and the temperature of exhaust gases. In this study, the radical combustion process has been established using a commercial 100 c.c. two-stroke engine. Engine operating parameters like fuel consumption, emission levels, and exhaust temperature have been studied at different running conditions (load, engine speed, and exhaust port throttling).

2. MECHANISM OF RADICAL COMBUSTION

Chain reactions are the most common type of chemical reactions. They consist of a series of consecutive, competitive and opposing reaction steps with different reaction rate constants. These complex chemical reactions occur in all combustion processes are mostly chain-branching reaction which is affected by the reaction environment. Therefore, it is not easy to ascertain whether the radicals are formed by thermal decomposition of the fuel or by oxidation or both.

The chain-branching reaction becomes sufficiently frequent, when compared to the rate of removal of hydrogen atoms, to cause multiplication of free valences and explosion when it reached a certain temperature. In this reaction process, the most active species are called free radicals. In chemical terminology, unpaired electrons or bond-paired electrons, characterizes free radicals. When heating of the fuel is continued beyond the flash point, it reaches the ignition point where the fuel vapour burns continually although no pilot flame is applied. Combustion is an oxidization process in a spontaneous chemical reaction accompanied with a formation of a high heat. Fuel does not ignite until it reaches a definite temperature, which is both the ignition temperature and the initiating temperature for the chain reaction of the complete oxidation.

The main mechanism that causes the engine to run with radical combustion could be auto ignition, run-on, and chemical kinetics. Apart from the ignition processes introduced by the external source such as spark plug or pilot flames, there is a process called auto-ignition, (or sometimes referred to as self-ignition, spontaneous ignition or homogeneous ignition) without the external ignition source other than the hot vessel walls. There are three conditions that take place in homogeneous gas phase combustion which involve a large number and variety of different elemental reactions. These conditions are beginning with kinetic process, produce short lived and reactive intermediate radicals that propagate the overall mechanism, and terminate the kinetic process by forming stable products of combustion. In the first condition, it is mostly called the chain reaction as explained before. The second one is called the chain carriers, where the chemical reaction happens and produces the energy. High temperature oxidation chemistry in premixed homogeneous fuel air mixtures is initiated by elemental fuel pyrolysis reactions. The equations for the branching reactions that produce more active radicals than they consume, are given below.

Equation (1) and (2) show an oxygen atom and a hydroxyl radical are produced from the collision of a hydrogen atom with an oxygen molecule, whereas a hydrogen atom and hydroxyl radical are generated from the collision of an oxygen atom with a hydrogen molecule in the equation. The kinetics associated with the initial stages of an oxidation

process and induction delay period are functions of the initial reactant concentrations, temperature and pressure but are not the rate controlling steps of the overall kinetic mechanisms. Equation (3) and (4) show chain branching reactions that are responsible for the rapid propagation of the $H_2 - O_2$ reaction mechanism. These reactions are often referred to as being autocatalytic in that they create more intermediate radicals than they consume, thereby self-accelerating the reaction process.

In gasoline engine, although the main ignition of the mixture initiated by the spark and subsequently spreads over the unburned mixture, the flame spreading process may require several milliseconds to complete. Run-on is continued fired of an engine when the ignition is switched off after a period of operation. Typically, on switching off, the engine speed falls to a certain value, then rises briefly, falls again, and so continues. The accelerations gradually diminishing until eventually the speed falls below a lower limit and cannot recover.

Auto-ignition may occur if the charge spends long enough time at a high enough temperature and pressure. Thus, there is insufficient time for auto-ignition above a certain speed limit, as temperature and pressure fall. Even if auto-ignition does occurs, the engine will not complete another rotation unless there is sufficient flywheel energy to carry it over to the top of the next compression. So for a given flywheel inertia, there is a lower speed limit. Re-firing can be successful only within the region enclosed by the minimum carry over speed and the self-ignition limits. Activated radical combustion process will burn all the fuel inside the combustion chamber by using the active radical molecules that is formed in the exhaust gas. When hot exhaust gas remains in the cylinder, it contains a small percentage of active radical molecules; when these are combined with the incoming fuel charge, the resulting mixture begins to auto-ignite at lower temperature.

3. ENGINE TESTING AND EXHAUST PORT THROTTLING

A single cylinder, 100 cc direct scavenging, air cooled two-stroke SI engine was employed in the present investigation. This engine was coupled to water dynamometer for speed and torque measurements.

A computer exhaust analyzer was used to measure the unburned hydrocarbon (UHC), (NO_x) as a part per million (ppm), carbon monoxide (CO), carbon dioxide (CO_2) and Oxygen (O_2) as a percentage emission levels in the engine exhaust. Calibrated standard instrumentation swas used for air and fuel flow rates, and exhaust temperature measurement. An exhaust port throttling mechanism to control the amount of the exhaust gases flow out from the combustion chamber has been designed and fabricated.

Figure 1: The modified engine cylinder.

A sliding plate been fabricated and inserted through the cylinder wall to decrease the area of the exhaust port is seen in Figure 1. The controller was designed so that the sliding plate can move up and down.

The main aspects that considered in designing the exhaust port throttling mechanism is related to change the amount of exhaust gases to be recycled to the next cycle. This process is achieved by changing the exhaust port area and the opening timing of the exhaust port. The exhaust port area reduced by the sliding thin plate down through the exhaust port. For example closing the exhaust port by four turns means a reduction in the area by 2%. The exhaust port opening timing in the two-stroke engine is related to the crank timing when the piston uncovers the exhaust port during the power stroke (i.e. piston moving downwards) this will change the opening timing. The throttling plate pushed down through the exhaust port. The above changes in the exhaust port area and exhaust port opening timing are significant factors affecting scavenging efficiency, discharge ratio and charging ratio. Moreover the filling and the scavenging mechanisms will also affected by these changes.

Experiments were conducted with ignition system using a normal spark plug (normal run). Variable load tests were carried out at engine speed range of 1000 - 4500 rpm. In the second stage of the experiments, the modified engine was used. The exhaust port opening (area is 560 mm² was throttled in order to re-circulated (trap) part of the exhaust gases to the next cycle. Hence, radical combustion was achieved. The exhaust port area was reduced in steps (100 - 80%) and hence the engine performance was studied with radical combustion. The parameters to be measured and studied are the specific fuel consumption, engine power, exhaust temperature and exhaust gas emission contents.

Figure 2: Specific Fuel Consumption for SI Combustion and Radical Combustion; Engine Speed $N = 4000$ rpm.

Figure 3: Exhaust Temperature for SI Combustion and Radical Combustion; Engine Speed $N = 4000$ rpm.

Figure 4: UHC Emission for SI Combustion with Radical Combustion; Engine Speed $N = 4000$ rpm.

Figure 5: O_2 Emission for SI Combustion and Radical Combustion; Engine Speed $N = 4000$ rpm.

4. RESULT AND DISCUSSION COMPARISON STUDY BETWEEN SI AND RADICAL COMBUSTION:

The engine has been tested at speed range of 1000 to 4500 rpm with spark ignition combustion (normal run). However, after preliminary testing it was found that radical combustion could be achieved at a high engine speed range (i.e. 3500 to 4500 rpm). When engine was running on a radical combustion (spark off), the exhaust port area was throttled at constant engine speed and load until the combustion process was deteriorated. This paper presents a comparative study at engine speed of 4000 rpm, showing the performance parameters at different engine loads and radical combustion at different exhaust port throttling (related to exhaust port area reduction).

Figure 2 present the specific fuel consumption (SFC) at different loads with engine speed of 4000 rpm. It is observed that fuel consumption with radical combustion has been reduced by about 11 – 49.8 %. Maximum reduction was achieved at engine speed of 4000 rpm and at exhaust port throttling of about 16 mm (exhaust port reduction area is 8%). At this stage, it could be difficult to examine the reason for this significant reduction in fuel

consumption. However, this could be due to the fact that radical combustion initiated at various spots (zones) all over the combustion chamber and hence more efficient combustion was achieved. The above radical combustion started at locations where high-energy radicals initiate auto-ignition combustion.

Figure 3 compares the temperatures of the exhaust gases at normal running condition (spark ignition combustion) to radical combustion running condition. It is observed that when engine is running on radical combustion the exhaust gases temperature is lower over the entire load range. The maximum reduction in the exhaust emission temperature is observed to be 19%. The reduction in the exhaust temperature is due to the large amount of exhaust gases that trapped and recirculated in the cylinder. Hence trapping of the exhaust gases might act to dilute the mixture, lead to deplete the reaction and tend to recognizable decrease exhaust gas temperature.

It is observed from Figure 4 that the unburned hydrocarbon (UHC) emission is lower with the radical combustion at all engines running conditions. The reduction in the hydrocarbon emission is observed to be 66.8% at engine speed of 4000 rpm. The improvement in the hydrocarbon emission is due to the reduction in the exhaust port area, which changed the scavenging process. Also the reduction of hydrocarbon emission could be due to the increase in the exhaust gases trapped which contain active radical mixing with the incoming charge and act as a very well distributed heat source to ignite the surrounded fresh charge and burning the hydrocarbon efficiently. This is an important result as there is strict legislation on the hydrocarbon emission levels. Moreover, this will lead to an improvement in the fuel consumption.

The oxygen (O_2) percentage discharged with exhaust emission is presented in Figure 5. A substantial reduction in the oxygen percentage is observed from this Figure. The reduction is found to be 49.6% at engine speed of 4000 rpm. This is also an important result, which indicated that the radical combustion process is a complete combustion process with fewer misfires and less unburned air fuel pockets. This result also has its impact on fuel consumption during radical combustion process.

The nitrogen oxide (NO_x) emission part per million (ppm) is presented in Figure 6. In general, the nitrogen dioxide value is less with the radical combustion compared to the normal SI combustion at low loads. This is an expected result as NO_x is generally related to the combustion (exhaust) temperature. As stated before there was a reduction at about 20% in the exhaust temperature with radical combustion. However, at high loads the nitrogen oxide shows a tendency to increase with radical combustion. This result will be looked into in future studies.

Carbon dioxide (CO_2) percentage is presented in Figure 7. In general carbon dioxide percent appear to be higher with radical combustion compare to that with normal combustion. This observation could be due to the fact that the combustion process is more complete process with radical combustion. However, the better mixing of the radical contained in the trapped exhaust with the new charge gives more chance for complete combustion. Hence, this will lead to higher carbon dioxide percentage with radical process as seen in the figure below.

Figure 6: NO_x Emission for SI Combustion and Radical Combustion; Engine Speed $N = 4000$ rpm.

Figure 7: CO_2 Emission for SI Combustion and Radical Combustion; Engine Speed $N = 4000$ rpm.

5. CONCLUSION

A 100 cc two stroke engine (SI) has been tested at different running conditions i.e. engine speed of 3000, 3500, 4000 and 4500 rpm and loads for 0.5 – 2.5 Nm. The same engine, then modified with a new exhaust port throttling system is employed and tested. The radical combustion (Sparkless) has been achieved and studied at the same running conditions.

A comparison study for the engine performance has been carried between normal combustion and radical combustion. The radical combustion shows a significant improvement in the most parameters studied. These improvements are summarized:

The exhaust temperature decreases by 16.7% to 22.5% at all engine speeds and loads. Significant reduction in the fuel consumption, which is 11.1% to 49.8%, was achieved. A considerable reduction in the hydrocarbon emission of about 60.8% was achieved. This reduction means that the loss in the fresh air-fuel charge is less and the combustion process is complete. The oxygen percentage in the exhaust emission was observed to be lower by 41.7%.

Also, it is observed that carbon dioxide percentage is higher. This also could be an indication of more complete combustion. The nitrogen oxide, carbon dioxide emissions were found to be variable at different loads, speeds and exhaust port throttling. The parameters controlling these emissions will be studied in future work. A comprehensive study also

conducted for the effect of the exhaust port throttling on the Radical Combustion characteristics. The results of this study reveal that, there should be a certain value of exhaust port throttling required for each speed and load. This is an important aspect of commercialise design of the system.

More exhaust port throttling has a positive effect on exhaust temperature, and most of exhaust gas emission constituents (HC , NO_x , O_2 , CO , CO_2), which indicates a complete combustion, was achieved.

Further studies on the effect of fuel air ratio, compression ratio, combustion chamber and piston designs are under progress. The dynamics controller due to the variable speed and loads is being considered better than static controller. For future, development the dynamics controller could electronically activated.

Finally, it is reasonable to conclude that commercialization of this system could be of great benefit in terms of fuel consumption and exhaust emission reduction.

6. REFERENCES

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