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EXHAUST GAS TEMPERATURE FOR KNOCK DETECTION AND CONTROL IN SPARK IGNITION ENGINE

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Abstract—Knock is a major problem limiting the development of efficient and powerful engines in both design and operating stages. It is objectionable due to its damage on engine elements. Without knock, an engine can be designed to have a higher compression ratio, giving higher efficiency and power output. Since knock is a factor of concern, many researches have been done to eliminate and control knock. To date, knock has been detected using an accelerometer or an in-cylinder pressure transducer. These types of sensors have some drawbacks. In this paper, a new sensor for detecting knock is presented. It uses the exhaust gas temperature as an engine variable and utilizes the fact that this variable decreases a considerable amount when the engine goes into knock. Thus, be locating a temperature sensor at the exhaust port of the engine, the exhaust gas temperature can be measured, and the onset of knock can be detected. It is observed that, under knock conditions the exhaust gas temperature showed favorable results toward correlating engine knock with a drop in the exhaust gas temperature. Also, a suggested control system is presented in this paper. This system could be used in conjunction with the sensing system to move the engine away from the knocking regime.

Knock   Exhaust gas temperature   Temperature sensor   Control system

INTRODUCTION

Background

Knock is one of the most debated and least fully understood phenomena involved in the internal combustion engine. Considerable effort has been devoted to understanding the complex knock phenomenon, and many advances have been made in reducing knock. However, in spite of all the efforts, an adequate understanding of engine knock and the effects of engine parameters on knock is lacking. An increased understanding of this phenomenon could lead to reduced fuel consumption through engine design changes.

There are two generally accepted theories of knock, autoignition and detonation [1, 2]. The theory of autoignition assumes spontaneous combustion in a part of the combustion chamber farthest from the spark plug. This volume is referred to as the end gas. At the point where the temperature and pressure of the end gas exceed its autoignition point, the end gas would ignite spontaneously, starting at one or more points. A violent explosion will occur in the end gas, causing pressure waves to oscillate in the combustion chamber causing the pinging sound.

Detonation theory, on the other hand, assumes that knock occurs due to the propagation of the flame front that accelerates from the spark plug to the other end of the combustion chamber, engulfing the end gas at a supersonic speed and creating a shock wave or a detonation. The shock wave would then reflect from one cylinder wall to another at the combustion chamber resonant frequency. The impact pressures are short in duration but high in magnitude, causing the high pitched sound of knock.

In most cases, trace (light) knock is not harmful, while extremely heavy knock is objectionable both to the engine operator due to its nuisance noise and to the engine itself due to its damage on engine elements. Valve sticking, piston holding, piston erosion, piston ring breakage, and cylinder head gasket failure have been observed due to severe knock [3, 4].

Among the different forms of knock which occur in car operation, one usually distinguishes between acceleration knock and constant speed knock [5]. It is agreed that the acceleration knock is more a nuisance to the driver and the passengers than a real danger to the engine. On the other hand, constant speed knock can hardly be heard because it is drov ned out by various noises, but when it is maintained (high speed driving), it may completely dam.age the engine.

Detecting and controlling knock

There are many engine variables that affect knock for a given engine design, such as spark advance, engine speed, fuel–air ratio, inlet pressure and temperature, etc. Some of these variables can be used to control knock, while others cannot. Once the engine variables that affect knock are identified, knock should be controllable by adjusting these variables. Before doing so, knock must first be detected.

There is currently no totally satisfactory means of detecting knock in spark ignition engines. The most common type of knock sensor is a vibration sensor, the accelerometer, which uses the fact that the engine structure vibrates as it knocks [6, 7]. This sensor can be mounted on the external surface of the engine, usually on the cylinder head. The output of the accelerometer, which has a relationship to the vibration of the engine structure, is affected not only by the vibration due to the abnormal combustion of knock but also by other engine component noises. Such sensors are relatively good for detecting knock at low engine speeds only where there are few other sources of engine vibration. This is unfortunate, since at high speed, knock detection has to be more accurate and sensitive in order to prevent the high rate of engine damage.

A pressure transducer is another common type of knock sensor. This transducer measures the large pressure fluctuation in the cylinder during the knocking cycles. It can be mounted through the spark plug or flush on the cylinder wall. Such sensors work very well, but they are expensive, especially in individual cylinder control, where one pressure transducer must be installed in every

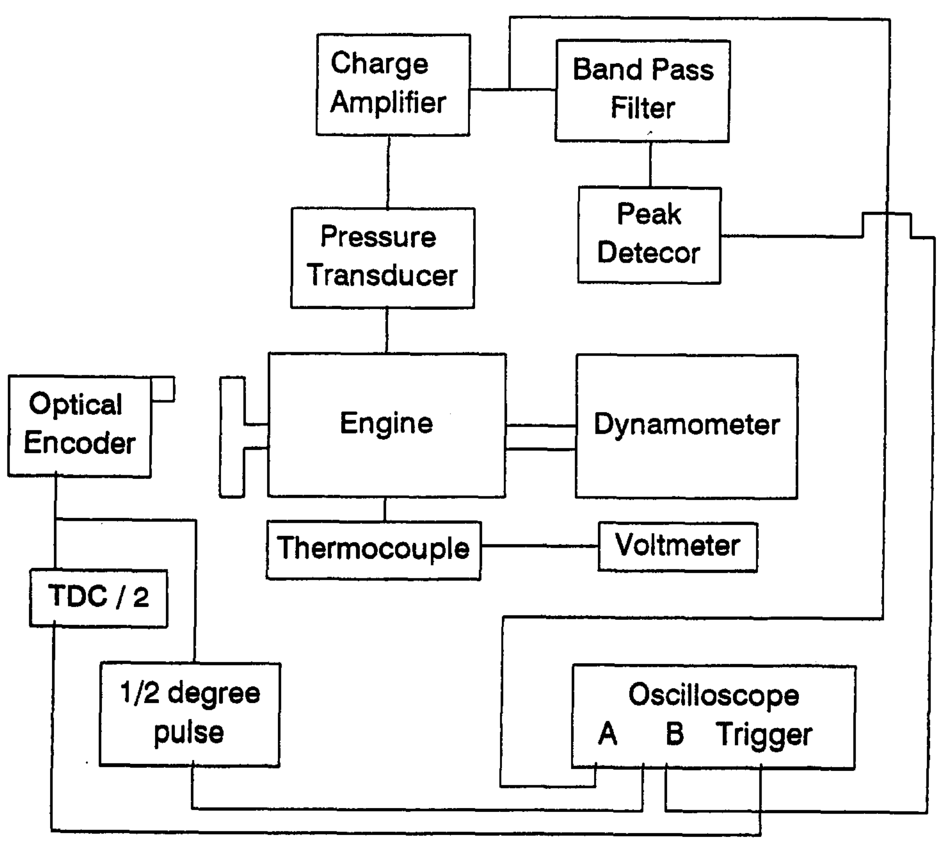

Fig. 1. Schematic diagram of the experimental set-up.

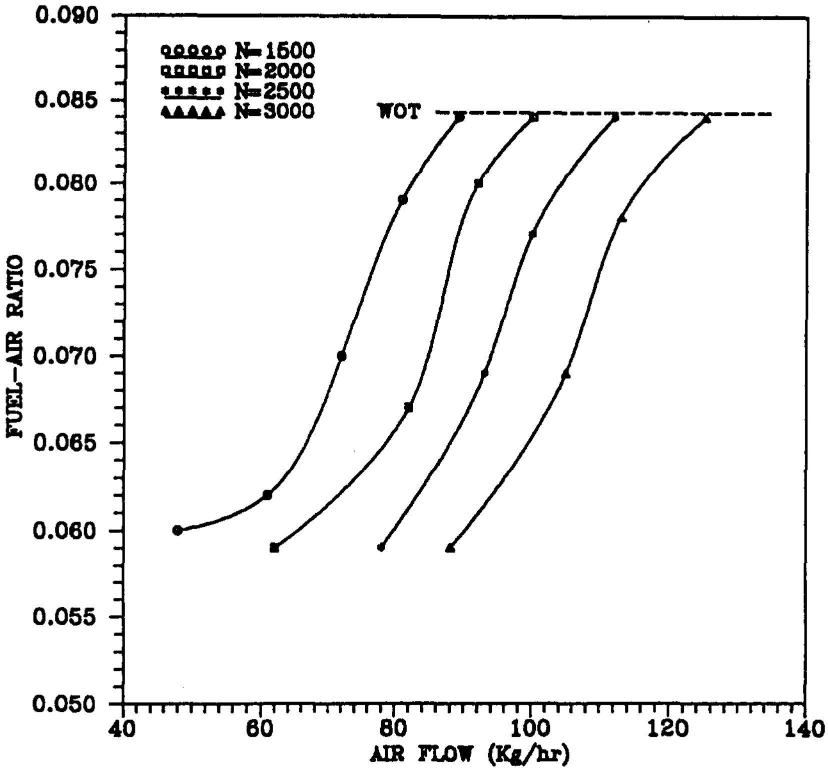

Fig. 2. Carburettor calibration.

cylinder. Also, due to the nature of its dynamic response, the sensor requires periodic cleaning and recalibration.

Once knock is detected, it can then be controlled by varying the variables that affect knock until the knock is eliminated. Knock is commonly controlled by two means: introducing higher quality fuel, and retarding the spark advance. The first one is the use of fuel that has a higher resistance to knock. The resistance to knock depends on the fuel's molecular size and structure. It is measured by a quantity called octane number (ON). In the second method, retarding the spark advance, if knock is present, reduces the maximum temperature and pressure of the gases in the cylinder during the engine cycle, therefore reducing the level of knock intensity. In turbocharged engines, where knock occurrence not only depends on spark timing but also on the boost pressure, decreasing both the timing and boost pressure are considered when knock is encountered.

To detect knock, it is preferable to use a sensor giving straight information of the overheating of the engine. In this investigation, the temperature of the exhaust gases was selected as the source and a thermocouple as a sensor. This sensor utilizes the fact that the exhaust temperature decreases a considerable amount when the engine goes into knock. Thus, knock is indicated whenever the drop in the exhaust temperature exceeds a certain threshold value, which is a function of engine speed and load. Also, a proposed control system is presented, which can be used in conjunction with this sensing system, to move the engine out of the knock region.

The suggested sensor should satisfy the following design criteria:

—sensor response within the time of one engine cycle;
—low cost;
—accessible and replaceable;
—ability to survive exhaust environment; and
—compact size and easy fit on most engines.

This technique for detecting knock could be efficient due to the following:

—the detection of knock is pure and the signal is not disturbed (the sensor is not affected by the level of engine noise);
—the detection of knock is very quick; and
—the technique is available for all varieties of engine.

EXPERIMENTAL METHOD

The experiment needed an engine that was capable of operating in knocking conditions for extended periods of time to obtain continuous data. The engine chosen for this work was a single cylinder, variable compression ratio engine. It was built with an iron piston to withstand high levels of knock intensity for extended periods. The knock intensity can be varied by changing the spark advance or compression ratio. The important characteristics of the engine are as follows:

Engine type: TD43	Inlet valve open: 10 deg. BTDC
Bore diameter: 9.5 cm	Inlet valve closes: 35 deg. ABDC
Stroke length: 8.2 cm	Exhaust valve open: 40 deg. BBDC
Fuel metering: Carburetor	Exhaust valve closed: 15 deg. ATDC

Engine speed can be controlled by an electrical dynamometer which is connected to the engine crankshaft. The cylinder pressure can be measured by a pressure transducer installed in the cylinder head.

First of all, it was necessary to confirm that knock could be detected by monitoring exhaust gas temperature. Therefore, it is required to determine how much the exhaust gas temperature decreases at the onset of knock compared to decreases observed during normal running conditions. The first set of experiments were performed on the engine under normal running conditions that have a

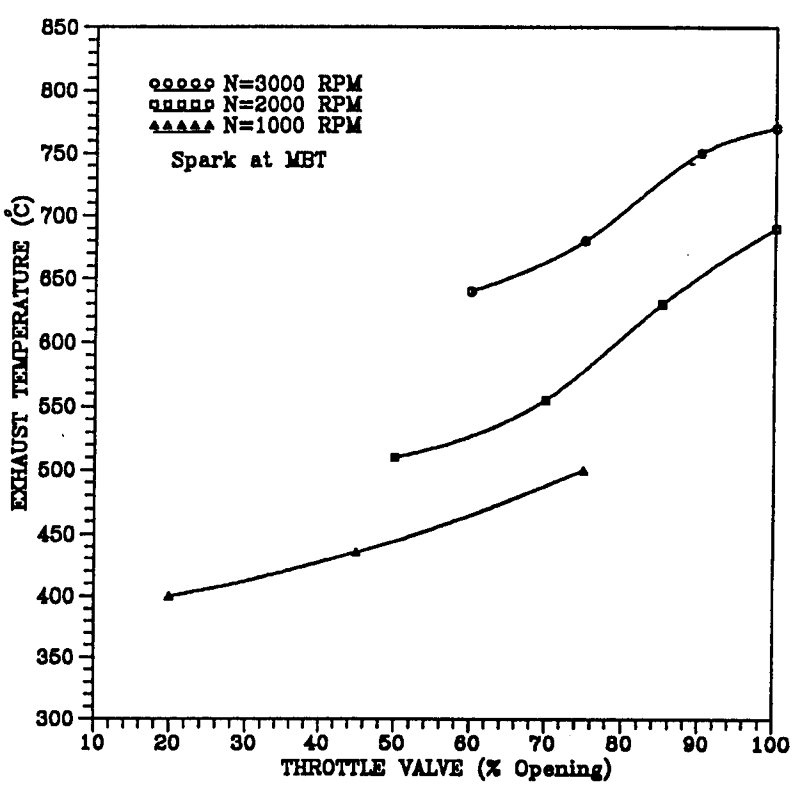

Fig. 3. Engine exhaust temperature against the throttle valve position at different engine speeds.

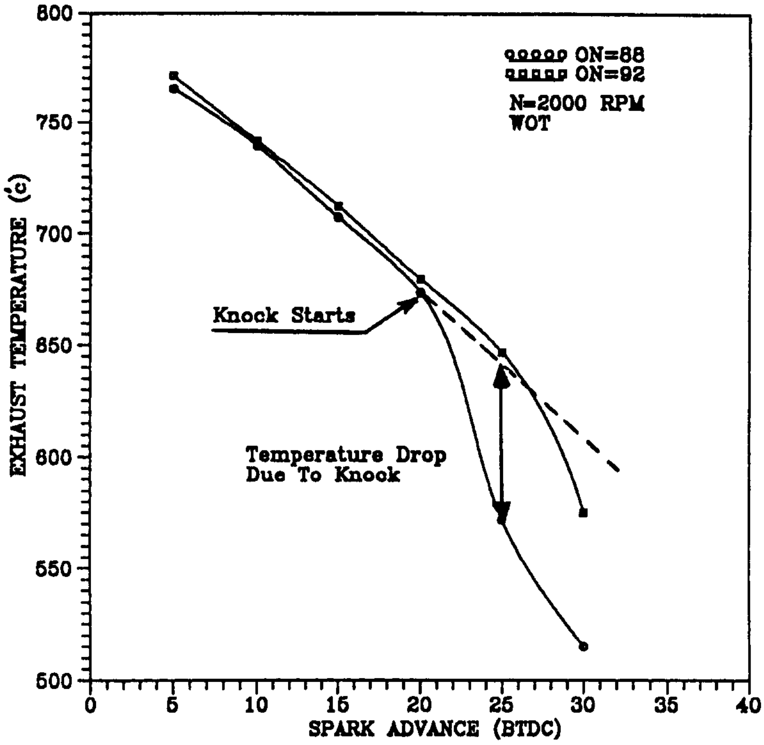

Fig. 4. The exhaust temperature at the exhaust port as a function of spark timing.

baseline as follows:

Compression ratio: 9	Fuel: gasoline (88 ON)
Spark advance: MBT	Oil temperature: 70°C
Inlet temperature: 20°C	Coolant temperature: 85°C

Engine speed: 1000–3500 rpm
Inlet pressure: Different percentage of the throttle valve opening up to wide open throttle (WOT)

Equivalence ratio: 0.8–1.3

The engine and the associated instrumentation are shown in Fig. 1.

The relation between the throttle valve opening (load) and the fuel–air ratio at different speeds was found, and the carburettor calibration is shown in Fig. 2. From this figure, if the engine is operating at a certain throttle valve opening and engine speed, the corresponding fuel–air ratio can be known.

The engine was operated at constant speed for different throttle valve openings, and the exhaust temperature was recorded at each condition of engine running. A chromel alumel, type K thermocouple was used for the exhaust temperature measurements. It was placed at a distance of 13 cm from the exhaust valve and has an operating temperature of −200 to 1260°C. Figure 3 shows a sample of the results for exhaust gas temperature at different engine speeds and throttle valve openings.

In the second set of experiments, the engine was operated under knock condition by advancing the spark timing. The spark timing of the engine was varied from about 5 to 30 deg. BTDC with a 5 deg. interval for 5 min. The temperature of the exhaust gases was then measured at the exhaust port at each interval. A sample of the results is shown in Fig. 4. It shows that, as the timing is advanced, the exhaust temperature drops slowly. If the timing is further advanced, the engine enters a knock region, and the exhaust temperature would drop faster.

The total temperature drop was observed to be as high as 250°C for advancing the spark timing from 5 to 30 deg. In the knock region, part of the temperature drop is due to advancement of the timing, and the other part is due to the onset of knock. To find the amount of temperature drop due to knock, another type of fuel of 92 ON was used. Then, the engine was run under the same conditions. The same test of spark advance was repeated, and the results are shown in the same plot of Fig. 4. It can be observed that the point where the knock starts is shifted to a higher spark advance compared to the 88 ON case. Also, the exhaust temperature falls rapidly when the engine enters the knocking region.

From the above observations, one can expect that, for the 88 ON case, if the engine is assumed to be knock-free at any spark timing, the drop in the exhaust temperature will follow the dotted line shown in the same plot. So, the actual drop in the exhaust temperature due to the onset of knock will be the difference in the temperature of the dotted line and that of the solid one, as shown in Fig. 4. This drop in the exhaust gas temperature is about 75°C for this condition.

Another method was used to find the actual temperature drop due to the onset of knock. A computer program that simulates the actual combustion process inside the engine cylinder was used to calculate the exhaust gas temperature. The program was run at different spark timings as in the above-mentioned conditions of 88 ON, and the results are shown in Fig. 5 in conjunction with the measured values. Knock is not considered in the program, therefore no sudden drop in the exhaust temperature is observed at the higher spark advance. Also, a difference between the measured values and the calculated one is observed, but they should have almost the same trend. This confirms that the curve of the measured values of exhaust gas temperature will follow the trend of the upper curve if the engine is knock-free.

The experiments were then repeated for different engine speeds and throttle valve openings under knock conditions. The knock intensity was measured for each condition of the experiments. Knock intensity is a parameter used to describe the severity of knock. The definitions of this parameter have not been standardized. Here, we defined it as the maximum amplitude of pressure rise from a band passed cylinder pressure signal [8]. Figure 1 shows a schematic diagram of the set up used to make the measurements of knock intensity. Primary items include an oscilloscope, a charge

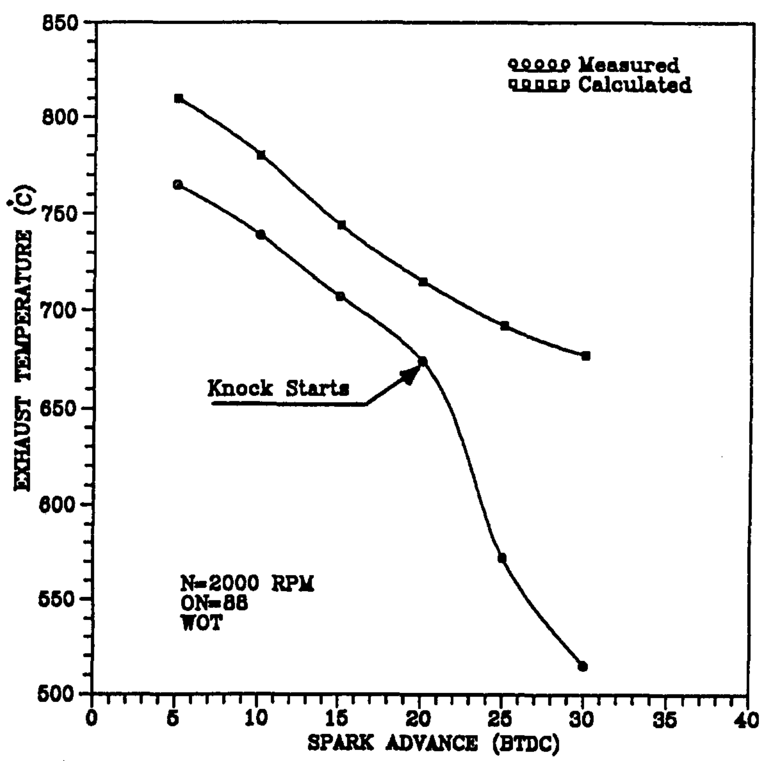

Fig. 5. Measured and calculated temperature at the exhaust port as a function of spark timing.

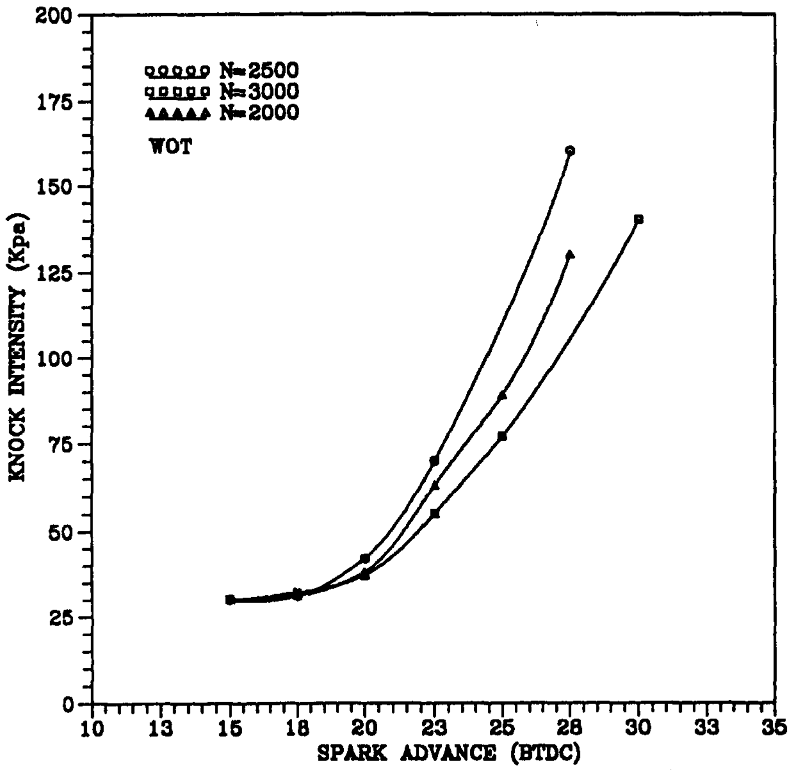

Fig. 6. Average values for 110 cycles of knock intensity as a function of engine speed.

amplifier, a pressure transducer, an encoder, a peak detector box, a divided by two box, and a band pass filter.

Knock intensity was calculated from the pressure measurements taken with a piezoelectric pressure transducer installed in the cylinder of the engine. The signal from the charge amplifier was passed through a band pass filter. The filter was centered at 6 KHz frequency, which is approximately the resonant frequency of the combustion chamber. This filtering effectively removed the non-knocking cylinder pressure history as well as higher frequency acoustical modes and high frequency noise. The resulting knock pressure signal consisted of the pressure oscillations resulting from knock occurrence. Only the peaks are determined by a peak detector. Then, the maximum amplitude from the filtered signal was taken as a measure of the knock intensity.

An average value for 110 cycles of knock intensity was taken at each condition. This average was varied from 20 kPa at normal combustion to 200 kPa at heavy knock. Samples of the results are shown in Figs 6 and 7. It was found that the highest knock intensity occurs at the region where the temperature drop of the exhaust gas is the largest. From this information, a correlation between knock intensity and the drop in exhaust gas temperature can be predicted.

DISCUSSION

Figures 4 and 5 confirm that the exhaust gas temperature decreases by about 75°C as a result of knock at wide open throttle and 200 rpm condition. This fact seems very appealing, since this drop in temperature can be used to detect knock in spark ignition engines. The reason for this drop in exhaust temperature is that pressure waves, as a result of knock, modify thermal exchanges at the walls of the combustion chamber. The heat carried away by the cooling system increases and, consequently, the temperature of the exhaust gases decreases. It was found that, under heavy knock, wall heat loss is three times higher than that of normal combustion [4]. When knock is very heavy, an overheating of the cylinder head will decrease the exhaust temperature. Under these

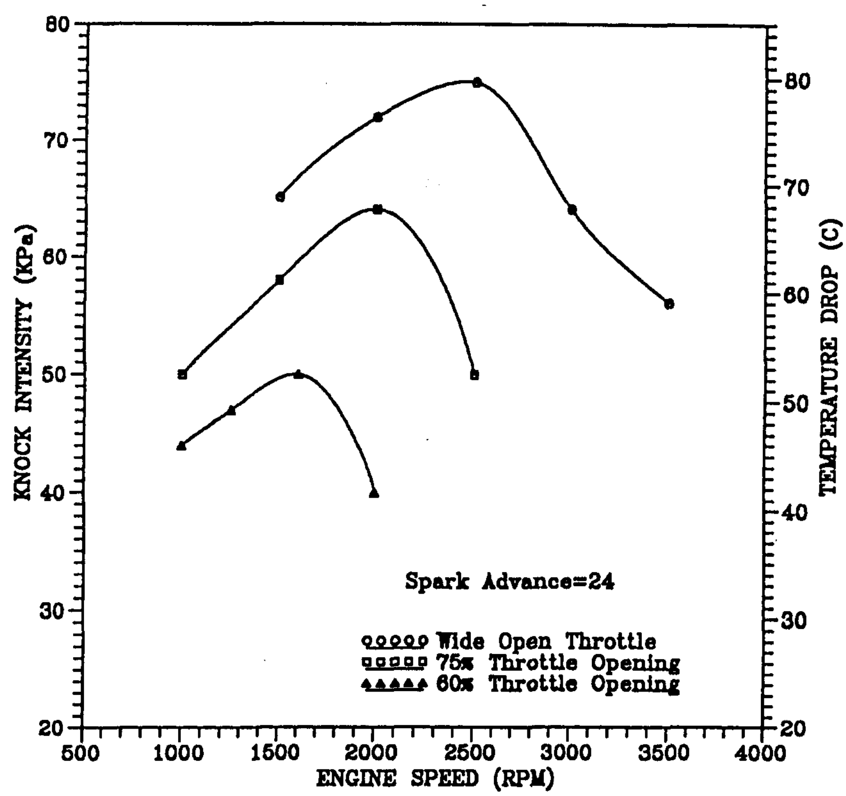

Fig. 7. Knock intensity and exhaust temperature drop against engine speeds for different throttle valve opening.

conditions, knock becomes heavier and heavier, and the uncontrolled running away knock could lead to severe engine damage.

Figure 7 shows the drop in the exhaust temperature and the knock intensity plotted against engine speed at different throttle valve openings. It can be seen that, for a certain percentage opening of the throttle valve, the knock intensity or the drop in the exhaust temperature increases as the engine speed increases up to a certain speed. This is because, at higher engine speed, the time for cooling the cylinder walls is smaller, so a higher end gas temperature inside the cylinder is expected. As the engine speed increases further, the knock intensity or the drop in the exhaust gas temperature decreases. This is because of the increase in the flame speed of the flame front due to the increase in the turbulence of the gases in the cylinder at high speeds. As a result, the flame front will reach the end gases before autoignition of these gases takes place.

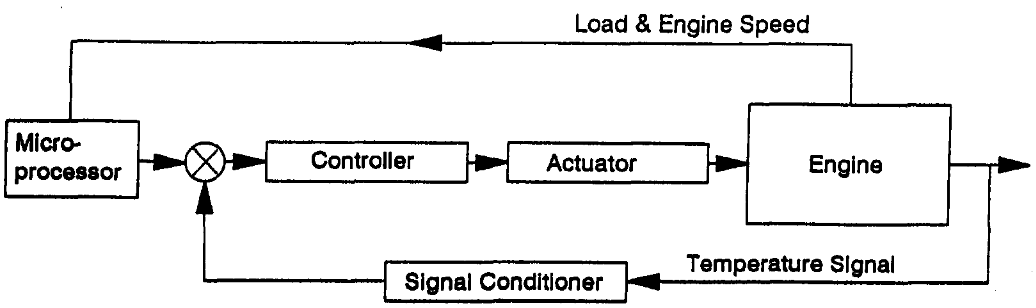

Fig. 8. Block diagram of the control system.

Also from Fig. 7, it can be seen that, for the same engine speed, as the percentage of the throttle mvalve opening increases, the knock intensity or the drop in the exhaust temperature increases. This is due to the higher cylinder pressure and temperature at higher load, so the end gases will have also a higher temperature; therefore, a higher knock intensity is the result.

KNOCK CONTROL

The knock sensor is an important part of the knock control system. It is intended to keep the variables that affect knock near the trace knock limit in order to achieve an engine output increase and improve fuel economy.

In order to control knock, the effect of the engine variables should be considered as discussed previously. Once the knock is detected by a thermocouple placed on the exhaust port of the engine cylinder, the temperature drop will be an indication to describe the severity of the knock intensity. This indication can be used to decide when knock is over a critical value at which it should be controlled. Knock can then be controlled by varying the variables that affect knock until knock is eliminated. For a given engine design and fuel quality (ON), which operates at a wide range of speed and load, knock is controlled by retarding the spark advance.

A performance map can be constructed and stored in a microprocessor to cover all possible engine operating conditions with the exhaust gas temperature. Then, a thermocouple in the exhaust port continuously measures the exhaust gas temperature and sends the signals to a control system. These measured values would then be compared to the values in the map for that engine condition of speed and intake manifold absolute pressure, which is equivalent to a load on the engine, to decide whether or not the engine is considered knock-free. If the map value is lower, then the engine is considered knock-free. The control system would then advance the timing in the ignition distributor through an actuator to obtain the maximum torque and minimum fuel consumption. The timing is advanced to an optimum spark timing which can be mapped in the ignition control system for a specific engine. As the engine is advanced into a knock region, the exhaust temperature will drop. Again, of the measured exhaust temperature is lower than the value for the new engine condition, then the base timing would retard itself taking the engine away from the knock region. Figure 8 shows a block diagram of the proposed closed loop knock control system.

In other words, the timing is retarded after finding the engine knocks, and then there is no more knocking after several engine cycles; the timing is then slowly advanced again in smaller steps. In the case of multi-cylinder engines, the exhaust temperature of the individual cylinder can be identified, then the spark advance adjustment can be applied independently for every cylinder.

The temperature signal obtained by the control system, which is measured by a thermocouple, will lag behind the actual temperature of the exhaust. This is because of the time constant of the thermocouple and the time that the exhaust gases require to travel from the exhaust valve to the measurement location. These lags have to be considered to obtain the actual exhaust temperature for every cycle. In this case, a fast response temperature sensor should be used for this application and should have a time constant of one cycle time at the most.

CONCLUSION

From the previous results, many new and interesting observations were obtained. This study confirmed that knock could be detected by monitoring exhaust gas temperature. Also, it is observed that, under knock conditions, exhaust gas temperature showed favorable results toward correlating engine knock with a drop in the exhaust temperature.

This technique for detecting knock could be efficient for the following reasons:

—the detection of knock is pure and can be made even at very high speed, since the signal cannot be affected by engine noise; and

—it is very quick and applicable for all types of engines.

The proposed knock control system presented here makes possible a further boosting of the compression ratio or allows the engine to operate in the maximum spark advance for maximum power of the spark ignition engine.

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