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THE EFFECTS OF WATER INJECTION
ON
NITROGEN OXIDES IN AUTOMOTIVE EXHAUST GAS

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PROJECT B-1-7-2

(In-House Report)

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INTRODUCTION

Use of water injection in engines dates back as far as the year 1880. During World War II, its use in aircraft engines was quite extensive. In all these past situations, its use has been exclusively to prevent knock. It had a secondary advantage on wartime aircraft and that was its cooling effect on the cylinder valves and the piston, which prolonged their service life at high performance levels. The present investigation of its use was undertaken to confirm its effect on reducing the NO_x emissions in automotive exhaust gases.

In a paper [1] given before the 53rd Annual Meeting of the APCA in 1960, the theory was discussed on the way in which injection can limit NO_x. Briefly, since NO_x formation is basically a function of the peak combustion temperature and fuel-air mixture ratio (availability of oxygen), any means which affect either of these will have a corresponding effect on the NO_x emissions. Reduction of NO_x by use of rich fuel mixtures are not desirable since this results in marked increase in hydrocarbons and carbon monoxide. With water, combustion temperatures are lowered by the heat used to vaporize, superheat, and finally dissociate the water, which limits the NO_x without significantly affecting the other emissions.

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(1) "Exhaust Gas Recirculation as a Method of Nitrogen Oxides Control in an Internal Combustion Engine" by R. D. Kopa and Kiroshi (Univ. of Calif.), APCA Paper 60-72, May, 1960.

This earlier work showed that at water to fuel ratios, on a weight basis, approaching unity, an 80 percent decrease in NO_x could be effected with only modest fuel consumption increases and power losses, usually in the order of 10 to 12 percent. Part throttle power losses, such as occurs at roadload conditions, are always recoverable with either a throttle adjustment and/or an ignition timing adjustment. In either of these cases, however, theoretically, changes will occur in the other components of the exhaust gas emissions, as previously shown by other investigators. For example, increasing either the fuel mixture ratio or advancing timing should cause an increase in the hydrocarbon concentration, with the latter having the more pronounced effect.

The objective in this project was to confirm previous findings for roadload conditions and to test an intermediate load value somewhat representative of a modest acceleration. Also, it was considered advisable to examine the effect of an alcohol-water mixture, at two different ratios, to observe the effects on emission, since alcohol would be used in cold months to prevent the water from freezing.

Conclusions

1. For part throttle operation with the engine tested, water injection ratios of 0.9 lbs. of water per lb. of fuel gave NO_x reductions of 75 to 80 percent without appreciable power losses or effects on hydrocarbon or carbon monoxide emissions.

2. Air-fuel mixture ratios are essentially constant over the range of injection ratios investigated.

3. Exhaust gas temperatures increase with increases in the injection ratio for part throttle operations and conversely, under wide open throttle conditions, they decrease. Although there is no precise explanation currently available, it does appear to be an enleanment phenomena for the former.

4. Power loss was a minimum with water-alcohol injection.

5. As part throttle operation approaches higher loads, the range of injection ratios that can be used becomes less due to their effect on power and hydrocarbon emissions.

TEST EQUIPMENT

Testing was conducted with a 1963 Chevrolet 283 cubic inch displacement engine and an Eaton Model 1519 DC dynamometer. Hydrocarbon emissions, CO, and CO_2 were monitored with Beckman NDIR equipment, Model type 15A. The NO_x concentrations were measured by the modified Saltzman technique; and oxygen by polarographic means with a Beckman #777 analyzer.

Fuel weight consumed was measured with a Cox weighing system, Model 402A, and the air used with a Meriam 6" laminar flow element. Engine ignition timing was determined with a Sun distributor advance meter, Model 214, and a timing light.

An explanation of the water injection equipment can best be accomplished by referring to the photograph in the appendix section. Basically, this is a commercial system sold for detonation control under the trade name "Octa-gane" and is made by the Engine Accessories Manufacturing Company of Los Angeles, California. Water is introduced through a plate sandwiched between the carburetor and intake manifold. Through incorporation of several toggle valves, the system could be made to operate whenever it was desired, as contrasted to its former use only at higher power conditions at wide open throttle. Air was introduced with the water at the large control valve to help atomize the water on discharge into the engine.

Test Procedure

Tests were conducted under the following conditions:

1. Roadloads equivalent to vehicle speeds from 30 to 70 mph, in 10 mph increments.
2. Intermediate loads (22" Hg. manifold pressure) for the same speed range as in step 1.
3. Wide open throttle at 30 and 50 mph.

For each of these operating conditions, the injection ratios tested ranged from 0.3 to 1.1 lbs. of water per lb. of fuel. Water-alcohol injection, was tested only at 50 mph roadload on two different mixture ratios (80/20 and 60/40 percent, respectively).

Changes in engine torque at constant speed settings were compensated for by throttle adjustments. Initially, spark timing changes were tried to correct or hold engine performance, but this was abandoned early because of its more adverse effect on hydrocarbon emissions.

Results

Graphical results on the effects of water or water-alcohol injection on emissions and engine performance are shown by the curves in the appendix section. In all cases, the greatest reduction in NO_x was obtained at the highest injection ratio (1.1). Through 60 mph, the NO_x reduction at this ratio averaged 84.5 percent. Above 60 mph, the gains in NO_x reduction became less because of the limitation on injection ratios that can be used with effecting power or the other emissions. At 70 mph, roadload, the maximum ratio was 0.5. For wide open throttle operation, the only ratio which gave an NO_x reduction was 0.3 and this was restricted to 30 mph. At 50 mph, wide open throttle, no reduction was made in either NO_x or hydrocarbon emissions, in fact both increased by 22 and 32 percent, respectively.

With respect to alcohol-water injection, the 20/80 percent solution decreased NO_x concentration by 80 percent with only a marginal increase of 4 percent in hydrocarbons. The 40/60 percent solution reduced NO_x by 84 percent but hydrocarbon concentration increased to 52%. Throttle adjustments to hold power with the alcohol mixtures were very slight as contrasted with straight water injection. With the latter, increases in manifold pressure become evident at about a 0.5 injection ratio. At the maximum ratio, the manifold pressure has usually increased between 1.5 to 2.0" Hg. above the baseline setting at any test condition.

Recommendations

That if interest exists, the following be given consideration:

1. Test an injection system on the road and/or under cycling conditions on the chassis dynamometer for emission evaluation and driveability.
2. Evaluate the continuous effects of water injection on engine durability.
3. Investigate the design and economic aspects of incorporating water on a passenger car to help establish its feasibility.
4. Determine what effect water injection has on specific groups of hydrocarbon under similar test conditions.

Discussion

Under throttled or roadload conditions, the effects of water injection on combustion are evidenced both by changes in manifold pressure and exhaust emissions. In regard to the latter, both NO_x and hydrocarbons are reduced by this injection, except at the highest ratios. At the higher ratios (0.9 to 1.1) hydrocarbons begin to increase rapidly indicating a progressive deterioration in combustion. The same effect also occurs at maximum power with any degree of injection. The increase in exhaust gas temperatures in the manifold accompanying injection at roadload conditions appears to be due to a slower burning rate it imparts, simulating a lean fuel mixture, and causes late burning in the exhaust manifold. This lower energy level of combustion reduces nitrogen fixation but also allows further oxidation of the unburned hydrocarbons before leaving the engine.

At higher load conditions above roadload, water injection has quite pronounced adverse effects on engine power and hydrocarbon emissions. Usually where water injection is used for maximum power conditions, such as in racing engines, its use is predicated on using leaner fuel mixtures than would be possible without it. Under these conditions, water serves not only for detonation control but also to cool the various combustion chamber parts.

The highest injection ratio which did not seriously affect performance up to 60 mph, roadload (2500 engine rpm), was 0.9. At this ratio, usually 75 to 80 percent reduction in NO_x was effected. Above it, hydrocarbon emissions and power loss increase too rapidly. In most cases, something approaching 2" Hg. increase in manifold pressure was required to maintain specified torque. With water-alcohol injection, this effect in power all but vanished and is probably explained by the energy contribution of the alcohol. From the results, it appears that 80/20 percent solution would be the more desirable of the two water-alcohol mixtures tested, because it gave approximately the same NO_x reduction but with very little increase in hydrocarbons. The 80/20 mixture, however, would probably not be sufficient for anti-freeze protection.

At part throttle operation, the air-fuel ratio remains essentially constant, although slight changes do occur in brake specific fuel consumption. However, from an over-all standpoint, fuel economy should not be too drastically affected with this control technique, unless the transient response of the engine has been somehow affected by it. Since an automatic arrangement of this system for part throttle operation does not currently exist, it was not possible to test this condition.

OTHER REFERENCES

1. "Detonation and Internal Coolants" by E. F. Obert, Northwestern University, SAE Quarterly Trans., January, 1948, Vol. 2-1.

2. "Antidetonation Injection" by C. H. Van Hartesveldt, Thompson Vitameter Corp., SAE Quarterly Trans., April, 1949, Vol. 3-2.

3. "Aviation Fuels and Their Effects on Engine Performance" (Manual of general information for U.S.A.F. and Navy), by the Ethyl Corp., 1951.