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ABSTRACT

A simple, relatively short and inexpensive screening test method has been developed for evaluation of available detergent/dispersant diesel fuel additives. The screening test is based on experiments of running a laboratory diesel engine in a pre-determined regime (load cycle). The engine is a single cylinder, 4-stroke DI, naturally aspirated and air cooled. It is coupled to a generator feeding electrical heaters as the load. The test rig is controlled electronically to enable fully automatic test bench operation, including start/stop, load change, emergency shut-down, etc.

The experiments were performed by running the engine on a reference base fuel and then the same fuel with different detergent additives. The nozzle of the fuel injector was checked for clogging by air flow measurements, using the ISO-4010 test rig.

The conclusions drawn from the analysis of the test results are that the method employed here for evaluating the detergent/dispersant additives is effective and has potential as a rapid screening test. It enables comparison between additives which have passed the recognized performance tests and selection of appropriate ones for experimental work in fleet tests or even for actual choice of suitable additives.

INTRODUCTION

The continuous demand of reducing emissions from diesel engines has led, in recent years, to increased interest in reformulated diesel fuels. It is well known that additives play a key role in the formulation of such fuels (called also premium or low emission). Diesel fuel additives have the potential of improving the quality of diesel fuels with regard to emissions, noise, engine performance and customer perception, whilst offering flexibility in the optimization of refinery production costs, [1 - 4].

An important property of the reformulated diesel fuel is its detergency, which is essential for maintaining good performance of the engine between periodic servicing. The use of detergent additives, that has become widespread in Europe during the last decade, was evoked by problems of injector nozzle fouling (or coking). Nozzle coking, induced by thermal degradation of fuel and crankcase lubricant components, and worsened by hot combustion gases, resulted in slower initial combustion, pressure rise delay in the cylinder with subsequent increased rate and higher peak pressures, [5]. These effects cause increased engine noise, emission of pollutants and fuel consumption. Detergent/dispersant additives containing surfactants, can prevent deposit formation ('keep clean'), as well as remove detrimental deposits already formed ('clean-up') in fuel injectors and thus yield and ensure good spray patterns characteristics, and maintain engine performance and pollutant emissions at the best levels possible for in-use engines, [4-7].

A range of substances is now suitable as detergent additives for diesel fuel: Amines, Imidazolines, Amides, Fatty Acid Succinimides, Polyalkylene Succinimides, Polyalkyl Amines, Polyether Amines, etc., [1,4].

The positive role of the detergent additives have led many automobile manufacturers to recommend their use in diesel fuel. For example, the French motor industry has set specific requirements for high quality fuels and these include fuel detergency performance for injector nozzles. The European Automobile Manufacturers Association also supports the use of injector cleanliness additives, [1].

Evaluating the performance of detergent/dispersant additives is an important aspect in the development of good quality products for use. Care must be taken when selecting additives in order to avoid any problems created by adverse side effects resulting from their addition to the base fuel, [8]. Examples of such detrimental effects are water and oil emulsification, deposit formation in critical areas of the engine and fuel system, corrosion, etc. Therefore, engine tests must be conducted for evaluating the improvements provided by the additives and ensuring that no adverse side effects occur.

The work presented in this paper has focused on the development of a simple short-duration test method for comparative evaluation of available detergent additives for diesel fuel which have passed the recognized performance tests.

EVALUATION TESTS OF DETERGENT ADDITIVES

Two widely recognized test methods are mainly employed now in Europe and the US for performance evaluation of detergent additives. These are briefly surveyed here for convenience. In Europe, the test which was developed by the Co-ordinating European Council, [9], is based on the widely used Peugeot XUD9 1.9L light duty IDI diesel engine. Like most engines of this kind, it is equipped with pyntle type injectors. The effectiveness of detergent/dispersant additives is evaluated by nozzle air flow check before and after the test. The engine is run for 6 hours at constant speed and load with 5 minutes idling prior to shut down.

The Cummins L-10 engine test, [10], is increasingly becoming accepted as the standard for performance evaluation of detergent additives for controlling nozzle fouling in DI engines. However, this test method requires an expensive test facility and therefore does not seem to be optimal for performing screening tests under all conditions. The test procedure is entirely different from the constant speed and load Peugeot IDI engine test. The engine is switched every 15 seconds between powered and motored load regimes and the duration of the test is much longer – 125 hours. The effectiveness of a detergent additive is determined by measuring nozzle flow loss and by visual inspection of deposits formation in the injector plungers, [5,10]. Evidently, the Cummins DI engine method requires a rather expensive test facility and substantial time devotion for the performance evaluation of additives.

It is worthwhile to note here that the potential customers may have a problem of how to decide which additive to select, among those in the market that have successfully passed the recognized performance tests. It is a techno-economical challenge to answer this question, and we can offer some possible solutions:

1. Asking the additive manufacturer to perform in his laboratory an evaluation test by one of the above methods, with the fuel used by the customer. This approach is quite prolonged and costly and introduces some uncertainty lab-to-lab correlations between test results.
2. Performing tests to compare additives by one of these standard methods in a single independent laboratory. Undoubtedly, this approach is free from above mentioned uncertainties, but it would be also very expensive.
3. Evaluating the effectiveness of additives by a simplified screening test. The idea here is to compare the performance of various additives by using a quicker method which does not require costly test bench and equipment.

The last approach seems to be justified at least when a rather fast and inexpensive decision is needed, based on experimental evidence. It has, indeed been adopted earlier for an IDI engine, e.g. [9, 12]. Attempts have also been made to develop short-duration tests for DI engines, [5,11, 13], but they require more expensive facilities. For example, the test of [5] is performed on an engine installed in the vehicle, so a roller dynamometer is needed.

As mentioned above, the goals of the work reported here were to develop a simple, short method and a test bench (based on a DI engine) for comparative evaluation of available detergent/dispersant diesel fuel additives. Then to use these test facilities and procedure for a screening test to compare between several additives and select one or more for experiments in the next stages of the research program: testing of heavy duty DI diesel engines, e.g. of buses, in vehicle fleet tests (such a fleet test has just been completed and its results will be soon published).

The experiments included running of a laboratory single-cylinder diesel engine at pre-determined operating cycle with various loads, using a reference base fuel and then the same fuel with six different additives which have passed the recognized performance tests. The nozzles of the fuel injector (a new one for each test) were checked for clogging by air flow measurements. Total fuel consumptions and total quantities of energy fed by the electric generator were recorded, and other parameters were monitored, e.g. temperatures and pressures.

The work described here is a part of a more general research program at the Technion Internal Combustion Engines Laboratory, concerning improvement of diesel engines performance and reducing emission of pollutants and fuel consumption. Previous results obtained in this program, dealing with the effects of ignition and combustion improvers and of diesel fuel stability, have already been published [14,15].

EXPERIMENTAL APPARATUS AND TEST PROCEDURE

The experimental work conducted for the development of the screening test was carried out in a test facility based on a diesel engine coupled to a generator feeding electrical heaters as the load. The engine, Petter AD-1, is a single-cylinder 4-stroke diesel, naturally aspirated, direct injection and air cooled. This configuration is appropriate for laboratory experiments of the type performed here, namely screening comparative tests, because it eliminates problems of alignment and influence of auxiliaries on the combustion process at relatively low facility cost.

The main engine specifications are listed in Table 1. It is equipped with a four-hole Lucas Bryce injection nozzle.

Table 1. Specifications of the Petter AD-1 Diesel Engine.

Bore (mm)	80
Stroke (mm)	73
Power (kW)	5.3
Compression ratio	18.8 : 1
Revolution (rpm)	3000
Injection pump	Bryce
Injection valve opening pressure (bar)	200

The generator is an A.C. Leroy Somer LSA35 M8, 5 kVA, 3000 rpm, compatible with the engine.

A schematic layout of the test bench is presented in Figure 1. The engine - generator system is completely controlled by an adjustable electronic control unit (ECU), which enables automatic start (by a 12V starter and battery), load change, stop, emergency shut-down and visual observation of the important parameters. In order to minimize high frequency vibrations of the engine, special shock absorbing mounts were installed.

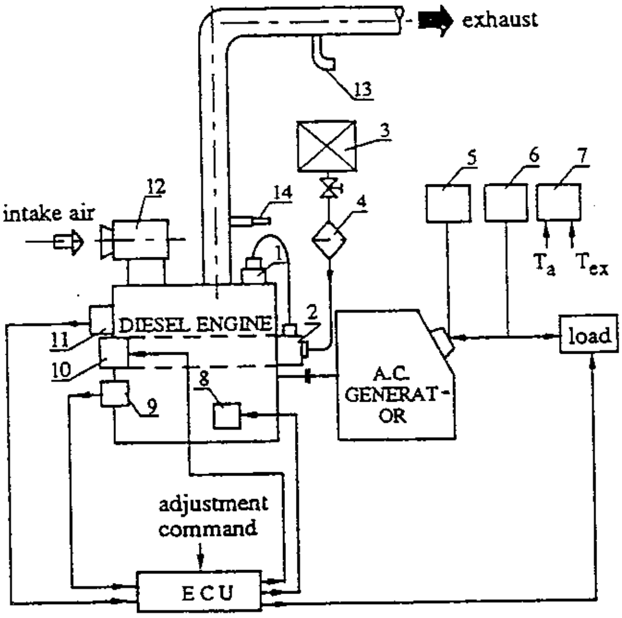

Figure 1: Test bench layout
1 - Injector; 2 - High pressure fuel pump; 3 - Fuel tank; 4 - Fuel filter; 5 - Frequency meter; 6 - kWh counter; 7 - Digital thermometer; 8 - Starter; 9 - Oil pressure unit; 10 - Rack position solenoid; 11 - Cooling air temperature transducer; 12 - Air filter; 13 - Exhaust gas sampling; 14 - Exhaust gas temperature sensor
ECU - Electronic Control Unit.

Special series of experiments had been carried out to develop and optimize the engine test cycle. The key points of optimization were: enough deposit build-up in the injector nozzle and minimal duration of the test. The procedure was developed according to the recommendations in [7,9,11], fitted to the performance characteristics of the Petter AD-1 engine. The operation cycle that was finally chosen consists of running the engine at constant speed of 3000 rpm and three loads of 0 (idle), 2.25 and 3.75 kW (about 45% and 75% of the peak load), governed by the ECU. A complete test lasted 23 hours, with 4 repeated cycles of 5 hour engine work: 10 min at idle after each of the 4 starts, then alternating the load at 3.75 and 2.25 kW for 10 min each, and 3 breaks of 1 hour, (Figure 2).

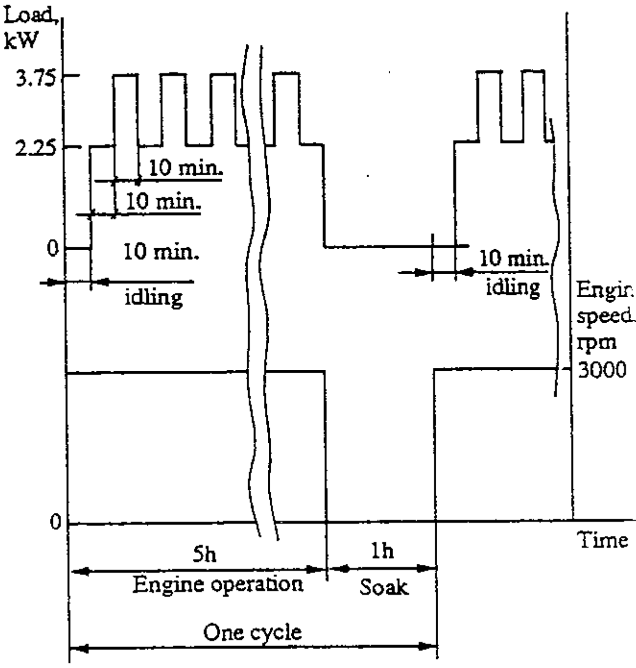

Figure 2: Diagram of the screening test operatin cycle.

The measurements, see also Figure 1, included generator frequency (giving the engine speed), total energy supplied by the generator to the electrical heaters load (kWh, by an electric energy counter), exhaust gas and ambient air temperatures, T_{ex} and T_a, and barometric pressure, p_b. The total fuel consumption during each test was measured by weighing the fuel in the tank before and after the test and the amount of returned fuel from the engine fuel line (accumulated in a flask). Smoke Bosch levels were measured in the beginning and end of each test, at the same load of 3.75 kW.

For every test a new nozzle injector was used. The nozzles were tested for clogging by air flow measurements with an experimental apparatus constructed according to the ISO-4010 Standard, [16], see Appendix.. The flow rate through the nozzle was measured for various needle lifts at the same imposed pressure difference, before (new nozzle) and after the test. The relative change of flow rates, expressed in percents, is the indication of clogging by deposits build-up during the whole test cycle. In order to check the state of tune of the injectors, they were re-assembled after the air flow test for each experiment and their opening pressure was tested. In order to prevent the influence of remaining fuel from one test to another, the engine was run 5 min at the idle, with a temporary injector, which was replaced by a new one after the fuel system was flushed. This time is sufficient for flushing the small volume fuel system of the engine.

DIESEL FUEL AND ADDITIVES

The base diesel fuel used in the screening tests, performed by using the procedure and facility described above, was a regular one, commercially sold in Israel in 1994 for public transportation. Its main properties are given in Table 2.

Table 2. Reference Fuel Characteristics

Fuel Property	Property Value
Density at 15°C, kg/m^3	840
Kinematic viscosity at 40°C, cSt	4.1
Calculated cetane index	54
Sulphur total, wt %	0.27
Flash point, °C	83
Distillation, 10% at °C 50% at °C 90% at °C	244 295 349

It is noted that the cetane index is rather high: 54. This leads, among other factors, to good combustion characteristics and relatively low rate of deposit build-up, [5]. Therefore, it was quite difficult to devise a short-time engine operation cycle which will yield significant nozzle clogging to enable accurate flow measurement (see above description of the test procedure).

Six different detergents/dispersant additives which are intended for reduction of deposits build-up in injectors were tested and compared. All are supposed to be both "clean up" and "keep clean", and hence to maintain close to design conditions of nozzle flow, exhaust emissions and fuel economy. The additives selected for the tests are all from established manufacturers, well known in the world market for quality and reliability of their products. They contain substances based on succinimide, amine and amide compounds. The treat rates of the additives (concentrations in the base fuel) used in the experiments are listed in Table 3. These were based on the manufacturers' recommendations for achieving optimum performance as regards reduction of deposits. It is noted that some manufacturers recommend other treat rates for maximum cost effectiveness.

Table 3. Detergent/Dispersant Additives Treat Rates.

Additive symbol	Treat rate
A1*	400 ppm
A2	200 ppm
A3	550 ppm
A4	350 ppm
A5	300 mg/kg
A6	500 ppm

* Additive A1 is a package,s containing detergent/dispersant and combustion catalyst substances.

RESULTS AND DISCUSSION

The experiments were carried out at the following ambient conditions: $T_a = 22 - 31°C$, $p_b = 99.4 - 99.8$ kPa. The exhaust gas temperature during the tests varied from 212 to 224° C at idle, 364 to 386° C at 2.25 kW and from 490 to 513 °C at 3.75 kW. The average total energy supplied by the generator during the whole cycle of one test was 53.49 kWh and remained very stable from test to test (standard deviation of ~ 1%).

The results of the air flow measurements of the injector nozzles for all the seven tests, with the reference base fuel and with the six additives, are illustrated in Figures 3,4 and Table 4. As can be seen from Figure 3 and Table 4, the relative change of the flow rate approaches zero and becomes independent of the needle lift when the latter is large. However, the formation of deposits typically affects more the needle tip and seat region, [5]. Therefore, significant changes are expected and were observed, indeed, in the lower range of needle lift, because then the flow is throttled and reduced more strongly. The measured results in Figure 3 are in agreement with the data of [5].

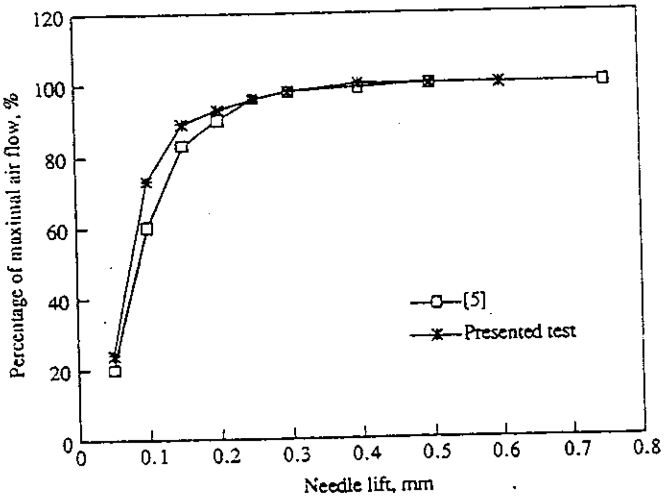

Figure 3: Air flow change in DI nozzles as function of needle lift.

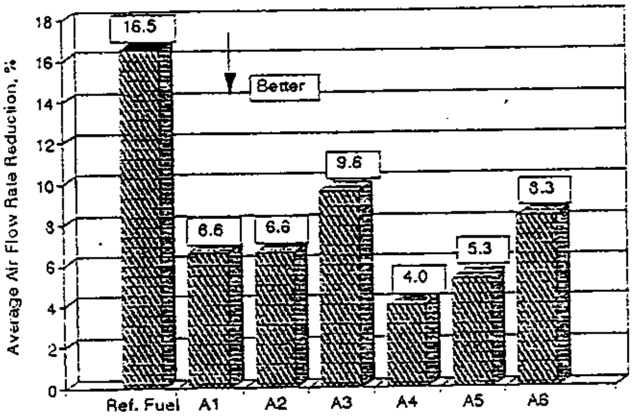

Figure 4: Average change in nozzle air flow rate over whole range of needle lift for the reference fuel and for the additives A1-A6.

Table 4. Results of Nozzle Air Flow Test

Needle lift, mm	Air flow reduction, %						
	Ref fuel	A1	A2	A3	A4	A5	A6
0.05	69	24	28	43	12	23	28
0.10	20	6.7	6.5	7.6	5.2	4.3	10
0.15	5.4	2.2	2.3	3.3	2.9	2.3	4.2
0.20	2.0	2.1	1.8	1.5	2.0	1.1	3.4
0.25	2.0	2.6	1.0	1.5	1.6	1.0	3.1
0.5 - 0.9	0.7	1.9	0	0.7 - 0	0.6 - 0	0	1.3 - 0.6

Figure 4 shows the average relative decrease of the air flow rate in the nozzles for the reference base fuel and the six additives, (average value of all lifts - see Table 4). The decrease of the flow rate in the reference test was, indeed, significant: 69% at 0.05 mm needle lift and 16.5% average. It is obvious from the results in Figures 3,4 and Table 4 that all the additives tested here were effective in reducing nozzle clogging. Additives A4 and A5 gave best results - averages of 4.0 and 5.3% flow reduction. As noted above, the additive A1 is not only detergent, but contains a combustion catalyst substance.

Visual checks of the injectors after each test revealed no plugged holes. The fuel tank and line were checked between the tests, in order to clean them if necessary so as to repeat the next test under the same conditions. No changes or deposits formation were discovered, which is one of several observations indicating compatibility of the additives.

As mentioned above, it is well known that injector deposits affect the fuel consumption of diesel engines. It was found that there is a trend of improving the mean specific fuel consumption by using the additives. The changes from the reference fuel were rather small (maximum of 0.79%) because of the relatively low deposits build-up in the injector nozzle during the test, but neither additive was worse than this fuel. The changes in measured smoke level reductions were small too, due to the same reasons.

It is finally noted that there is no doubt that in longer runs the injector nozzles which are more clogged would cause increase of fuel consumption and of smoke emission. The results of the tests described above provide a good measure for screening between additives on the basis of comparing the relative air flow changes that they cause.

SUMMARY AND CONCLUSIONS

The results presented above show that the method developed and employed here for evaluating the performance of detergent/dispersant additives is effective and has potential as a rapid screening test. It enables comparison between additives which have passed the recognized performance tests and selection of appropriate ones for continuation of tests in heavy duty diesel engines or vehicles. After gaining more experience with this method, it could serve for selecting additives for real use too. It should be realized that the actual choice will be based on cost considerations too.

As a summary of the screening tests results, the following conclusions can be drawn:

a) Detergent additives A4 and A5 gave the best results as regards reducing deposit build-up with the tendency of specific fuel consumption improvement.

b) No adverse side effects were observed in any of the experiments with the additive tested.

Based on these conclusions, one of the additives, A5, was used in the next stage of the research work, namely the fleet test with 10 urban and interurban buses, running one month with a reference fuel followed by one month with additized fuel. The results of this test will be published in the near future.

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APPENDIX: EVALUATION OF NOZZLE FOULING BY AIR FLOW TEST

The test system and procedure, developed for checking the condition of nozzles (fouling or clogging) by air flow, were designed according to Standard ISO-4010, [16]. Figure A1 is a schematic description of the test rig.

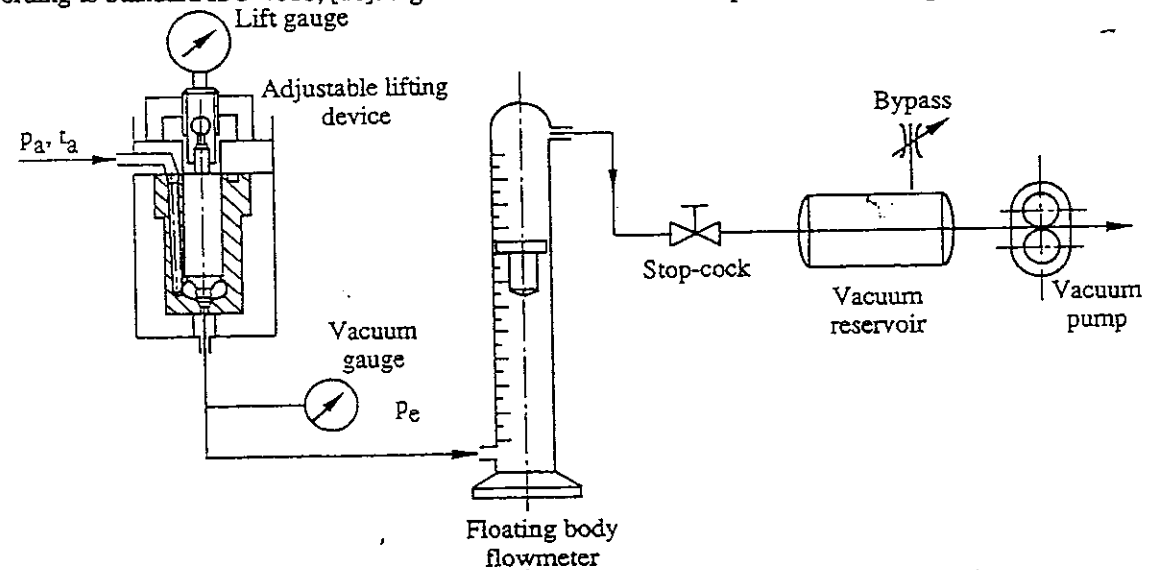

Figure A1: Schematic of the test bench for measuring air flow through fuel injector nozzles