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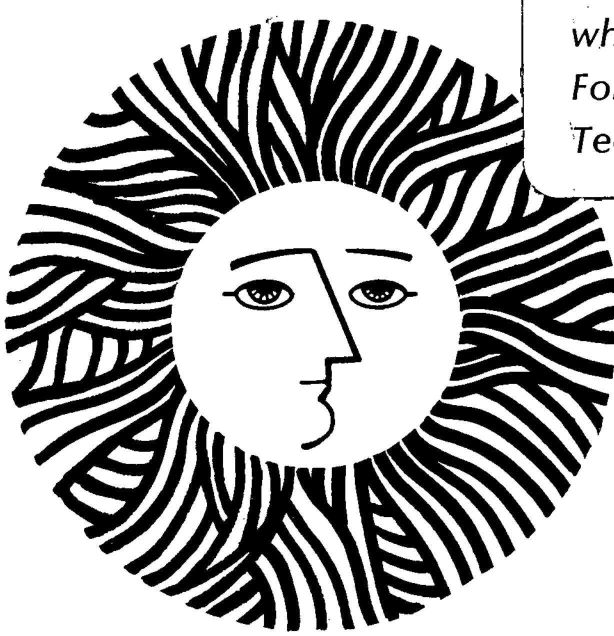

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PERFORMANCE OF WATER EMULSIFIED RESIDUAL FUELS IN A MEDIUM-SPEED DIESEL[1]

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ABSTRACT

Particulate and NO_x concentrations and thermal efficiency have been measured on a medium-speed, 2500 kW (3400-hp) diesel engine using diesel No. 2 reference fuel and three high viscosity residual fuels. The fuels were emulsified (without surfactant) at 0%-12% water addition (by volume) with droplet diameters of 2-5, 5-10, and 10-20 micrometers. No effects were detected as a result of different ranges of droplet diameter. Both NO_x concentration and thermal efficiency decreased as water level was increased: about 10%-15% for NO_x and less than 1.5% for thermal efficiency (at 12% water). The engine emits about 0.051 gm/MJ (0.14 gm/bhp-hr) particulate for diesel No. 2 and about 0.19 gm/MJ (0.50 bhp-hr) for both the 3500 and 5000 Seconds Redwood International (SRI) viscosity residual fuels. Contrary to what might have been expected, particulate formation with 12% water addition was higher than with 4% water addition or dry residual fuels. By x-ray fluorescence analysis it was determined that the particulate matter contained about 9% ash when using diesel No. 2 and 30% ash when using the residual fuels.

NOMENCLATURE AND ABBREVIATIONS

bhp	Brake horsepower
bmep	Brake mean effective pressure
btdc	Before top dead center
rpm	Revolutions per minute

INTRODUCTION

Combustion equipment manufacturers and researchers have investigated the potential advantages of water injected into combustion systems since late in the eightteenth century.(1)* Originally, water addition was desirable for lowering operating system temperatures. More recently, however, Kopa, et al. (2) suggested that water addition would reduce combustion generated nitrogen oxides (NO_x). Production of NO_x has been found to be markedly reduced with the presence of water in compression ignition engines (3-7). A slight increase in thermal efficiency with water addition has also been observed.

About 25 years ago Russian researchers (8) postulated that small diameter water droplets dispersed in fuel would improve fuel atomization. This occurs by the water boiling inside the fuel droplet preceding fuel vaporization. They theorized that the vaporizing water would shatter the fuel droplet thereby increasing the surface area available for evaporation. Several bench experiments have verified this claim (5,8,9). Conclusive evidence of shattering fuel droplets is not available in engines. However, several engine results have followed predictions obtained from this theory (3,4,7).

Transamerica Delaval, Inc. (TDI) with partial support from the Maritime Administration (MARAD) of the Department of Transportation has evaluated water emulsified heavy residual fuels in the six-cylinder version of their Enterprise medium-speed diesel engine line. As part of the program, Lawrence Berkeley Laboratory (LBL) collected and analyzed particulate samples for mass and elemental composition. TDI tested diesel No. 2 reference fuel and three residual fuels at 4 levels of water addition, 3 droplet diameters, and at 50%, 75%, and 100% engine load conditions. The purpose of this program was to identify the most effective level of water emulsification and water droplet diameter for each of the fuels in accomplishing the following:

(1) increase thermal efficiency,

(2) reduce particulate emissions, and

(3) reduce NO_x emissions.

In addition, the engine was disassembled and inspected for engine wear after completion of the entire test program.

EXPERIMENTAL METHOD

Three residual fuels with viscosities of 1500, 3500, and 5000 Seconds Redwood International (SRI)[2] were compared to diesel No. 2 as the reference fuel. Table I contains information about typical fuel batches. In addition, mass spectrometer results on the diesel No. 2 and 5000 SRI fuels have been reported. Except for diesel No. 2 which is sufficiently pumpable, all the fuels were heated in order that the kinematic viscosity was nearly 70 Saybolt Universal Seconds. The residual fuels were tested without water and with 4%, 8%, and 12% by volume addition of water. Another parameter varied was the water droplet diameter emulsified in the fuel. Most of the emulsified fuels were held inside the 2-5, 5-10, or 10-20 micrometer droplet size ranges. The diameter was verified by photomicrographs at 1000 power.

The engine used in this program is briefly described in Table II.

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[1]Parts of this paper are taken from the report "Emission Characteristics of a Medium-Speed Diesel Using Water Emulsified Residual Fuels", by D.D. Brehob, F. Robben, R.F. Sawyer, and K.R. Pearce, Lawrence Berkeley Laboratory Report No. 14987 which was presented at the Fall 1982 Meeting of the Western States Section, The Combustion Institute.

*Numbers in parentheses denote references listed at the end of the paper.

[2]SRI is nearly the same as Saybolt Universal Seconds.

TABLE I

FUEL PROPERTIES FOR TYPICAL BATCHES

Fuel	Diesel No. 2	1500 SRI	3500 SRI	5000 SRI
Specific Gravity	0.86	0.98	0.98	0.98
Viscosity (38°C) (m^2/sec X 10^6)	4.0	340	850	1200
Cetane Number	52	23	26	26
Calorific Value (MJ/kg)	46	43	43	43
Aluminum (ppm)	<1	*	*	<1
Silicon (ppm)	2	*	*	1
Sulfur (ppm)	1300	11000	10000	7800
Calcium (ppm)	20	*	*	405
Vanadium (ppm)	<1	55	80	55
Nickel (ppm)	<1	*	*	45

* No analysis for this element was made.

TABLE II

DESCRIPTION OF ENGINE

MANUFACTURER: Engine and Compressor Division of Transamerica Delaval, Inc.

LOCATION OF MANUFACTURER: Oakland, California

MODEL: DSR-46

CYCLE: Four Stroke Diesel

NUMBER OF CYLINDERS: Six

BORE X STROKE: 432 mm X 533 mm (17 in X 21 in)

COMPRESSION RATIO: 11.6:1

BMEP: 1.55 MPa (225 psi) at full load

SHAFT POWER: 2500 kW (3400-hp) at full load

SHAFT SPEED: 450 RPM

PRESSURE RATIO ACROSS TURBOCHARGER: 2.8 at full load

OTHER FEATURES: Intercooler after Turbocharger
Direct Fuel Injection
Two-Piece Trunk-Type Piston
Four Valves per Cylinder

The DSR-46 manufactured by TDI is a 1.55 MPa (225 psi) bmep, medium-speed (450 rpm) diesel engine. This engine line is found in marine and stationary power generation applications. Figure 1 schematically shows the equipment used in this program: generator, exhaust emissions analyzers, particulate sampler, emulsor, etc.

The engine's thermal efficiency was determined by comparing the electrical energy produced by the engine to the fuel energy input. The engine turned a generator (of known efficiency) which produced electrical power. This power was dissipated in a water rheostat. The rheostat's resistance was increased by raising the water level in the tank containing the electrodes. The power meter and the other equipment is shown in Figure 1. The fuel energy input was calculated by measuring fuel consumption rate by a positive displacement flowmeter and multiplying by the calorific value of the fuel. The water/fuel ratio was set by adjusting the flowrates of both fluids as determined by the flowmeters. In addition, water/fuel ratio was periodically verified by boiling off the water from the emulsified fuel and weighing. The two methods differed by 1.0% or less in water/fuel ratio.

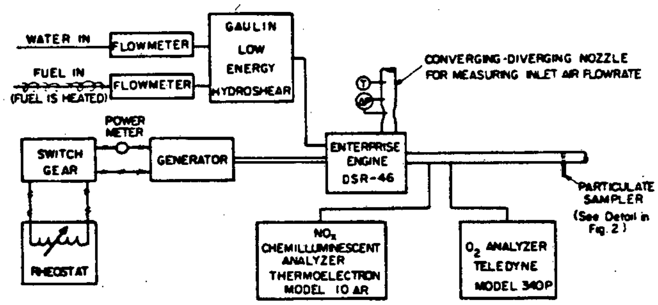

Figure 1: Schematic of test engine with associated measurement equipment.

The injection pumps and the nozzle holders were manufactured by the Bendix Corp. The model numbers are FDXE-26 and H4L-400, respectively. The plungers in the injection pump were 26 mm in diameter. The spray tip had 8-0.599 mm holes with a wall thickness of 1.8 mm.

The emulsor unit operates by introducing the fluids tangentially in a conical cavity producing shear. This prototype model, called the Low Energy Hydroshear, can provide water flowrates up to 630 mL/sec (10 gal/min) with a pressure drop of 1.9 MPa (280 psig) for 2-5 micrometer diameter droplets and a 70 kPa (10 psig) drop for producing 10-20 micrometer droplets. No surfactant was required since the emulsified fuel was immediately injected into the engine.

NO_x concentrations were measured by a ThermoElectron chemiluminescent analyzer. All measurements are normalized to 15% oxygen concentration in the exhaust. This gives:

NO_x (corrected) = 5.9 X NO_x(as read)/(20.9 - % O_2(as read)).

The exhaust O_2 concentration was measured by a Teledyne O_2 analyzer.

A schematic of the particulate sampling apparatus is shown in Figure 2. The sampling probe in the exhaust stack contains 15-6.4 mm. diameter holes spaced so as to provide a mean sample of the exhaust. Approximately 0.05% of the exhaust gas was mixed with ambient air in proportions of 1 part exhaust gas to 10-20 parts air. At these dilution ratios, the temperature at the filter was lower than 50°C. A portion of this well mixed, diluted exhaust sample was then pumped through a filter by a constant mass flowrate (1 gm/sec) vacuum pump. The remainder of the diluted exhaust was vented to the atmosphere. No attempt was made to sample isokinetically because it is not an important consideration for collecting submicron particles (10).

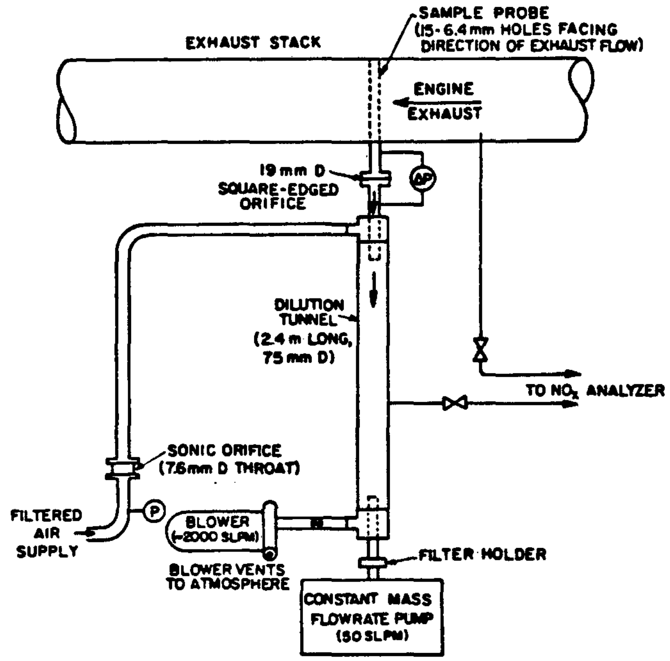

Figure 2: Schematic of diesel particulate sampler.

The level of dilution achieved was measured in two ways:

(1) direct measurement of the flowrate through the exhaust probe and the flowrate of the dilution air.

(2) comparison of the NO_x concentration in the exhaust stack with the NO_x concentration in the diluted exhaust sample as measured by the chemiluminescent analyzer.

Measurement of the exhaust flowrate with the square-edged orifice shown schematically in Figure 2 was not satisfactory. With no flow, the pressure gauge indicated a pressure difference across the orifice of about 25 mm water which is on the order of half of the full scale reading. At the sampling probe location downstream of the turbocharger, large pressure fluctuations existed. A dynamic effect as a result of these pressure fluctuations appeared to be responsible for pressure differences across the orifice indicating a different flowrate than under steady flow, steady pressure calibration conditions. Because of these problems, all data reduction was based on the NO_x technique for determining dilution ratio.

The samples were collected on two micrometer pore size, teflon coated filters obtained from the Ghia Corporation, Pleasanton, CA. The 37 mm diameter filters were mounted in a polyester frame by Ghia. These filters are compatible with an automated device developed at LBL for measuring aerosol mass. The beta gauge (11) operates by measuring the attenuation of beta particles caused by the filter substrate and the particles collected on the filter. The filter is placed between a radioactive source, namely ^{147}Pm, and a detector. The difference in attenuation before and after particle collection yields mass. The precision of this instrument is +/-50 ng/mm^2 with a maximum loading of about 2000 ng/mm^2. Careful measurements with a microbalance can give slightly better precision.[3] However, the beta gauge has several significant advantages which have proven it to be a powerful tool in this program:

(1) Over 100 filters/8 hour day can be measured by the automated beta gauge.

(2) Filter handling, storage, removal, and installation are greatly facilitated by the polystyrene frame. Also, the risk of contamination is minimized.

(3) The teflon coated filters absorb a negligible amount of water making desiccation of the filters unnecessary.

The elemental composition of the particulates was measured by x-ray fluorescence. Each filter was scanned for concentration of 30 elements with molecular weights greater than magnesium. In addition, the diesel No. 2 and 5000 SRI fuels were analyzed by a mass spectrometer for metals content.

Upon completion of the emulsified fuels test program, various engine components were inspected for deposit build-up and measured for wear. The following were measured before and after testing: cylinder liners, piston skirts, piston rings, connecting rod bearings, valve stems, and valve guides. Also, the following components were inspected for deposits: cylinder heads, intake and exhaust ports, turbocharger, cylinder liners, piston lands and grooves, piston rings, injector nozzle assemblies, and fuel injection pump.

RESULTS

Nitrogen oxides and thermal efficiency

Figures 3 and 4 show thermal efficiency and NO_x concentrations as a function of water addition for the 3500 and 5000 SRI fuels at 100% load. Since no differences were detected as a function of water droplet diameter, each data point is an average over all droplet sizes. Figures 3 and 4 are subdivided by injection timing. Notice that for each fuel and injection timing there is a trend toward lower thermal efficiency and lower NO_x emission with increasing water content: 1.5% and 10-15% reductions, respectively, at 12% water. The repeatability for any given water level is about 3% in thermal efficiency and 10% in NO_x concentration. Thus, verification of these trends in thermal efficiency by proving statistical significance is not possible.

The chemiluminescent analyzer was not available when testing on the diesel No. 2 or the 1500 SRI fuels. Thus, NO_x information was not obtained. However, Figure 5 shows that the thermal efficiency tends to drop slightly with increasing water level just as that found with the other fuels. The 1500 SRI fuel results in Figure 5B show the expected trend: thermal efficiency increases with advanced timing.

[3]Actually the precision is +/-30 ng/mm^2 per individual measurement. But, both a tare and final measurement are required. This results in a +/-50 ng/mm^2 total uncertaintly.

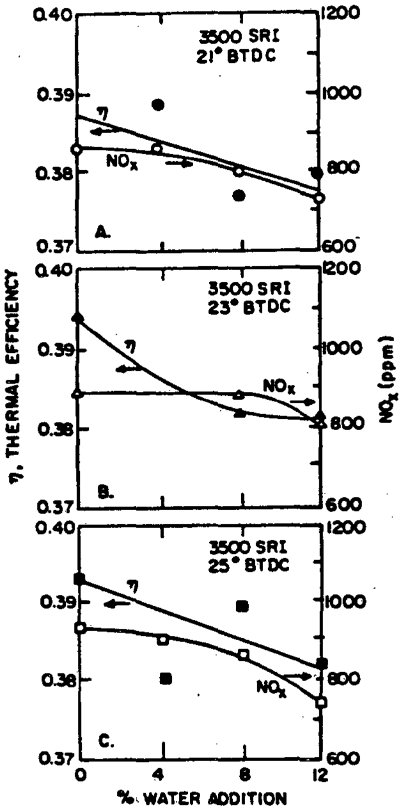

Figure 3: NO_x and thermal efficiency response to water addition with 3500 SRI fuel at three injection timings.

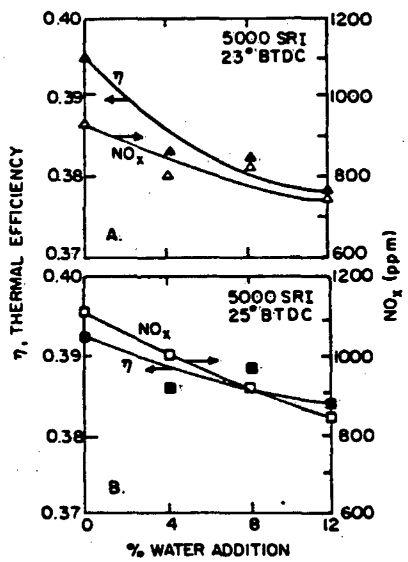

Figure 4: NO_x and thermal efficiency response to water addition with 5000 SRI fuel at two injection timings.

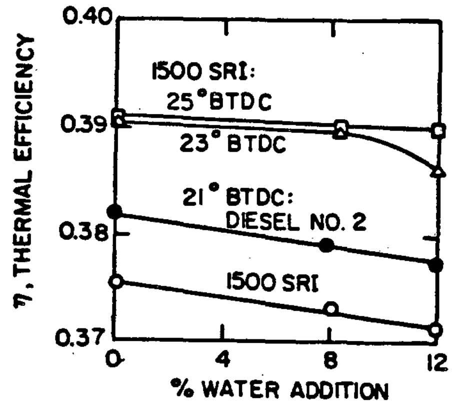

Figure 5: Thermal efficiency response to water addition with two fuels at varying injection timings.

Thermal efficiency and NO_x for 50% and 75% loads are not presented here. The injection pump used had a variable start of injection at loads less than about 85%. Since the rate of injection was constant for all tests, at part loads both the start and the end of injection timing varied with increasing water concentrations in the fuel. For example, at 75% load, the start of injection is 3 CAD (degrees crank angle) more advanced with 12% water than with neat fuel. Because a helix which would provide a constant start of injection at all load conditions was not available, the part load NO_x and thermal efficiency data are less meaningful. It should also be pointed out that the rate of injection was not varied. Thus, at 100% load the injection duration is increased by about 7 CAD with 12% water compared with no water addition.

Particulates

Each bar in figures 6 and 8-10 represents the average of all particulate samples taken at each point. The vertical line through the bar indicates the 90% confidence interval for the mean of that measurement, that is, the range in which the true mean lies at 90% assuredness. Taking into consideration the variability of these measurements and the number of samples collected, the true mean at each test condition can be estimated to be within about 25% of the measured mean.

The diesel No. 2 reference fuel emitted approximately 0.051 gm/MJ (0.14 gm/bhp-hr) of particulate. Particulate formation at 100% load was higher than at either 50% or 75% load (statistically significant at the 90% confidence level). This difference is depicted in Figure 6.

Figure 6 also shows comparisons between diesel No. 2 reference and two residual fuels (with no water addition). The 3500 and 5000 SRI viscosity fuels were indistinguishable in particulate formation. However, these residual fuels generate about four times as much particulate as the diesel No. 2 reference fuel, i.e., approximately 0.19 gm/MJ (0.50 gm/bhp-hr). No trends as a function of engine load were observed for either residual fuel.

Table III shows average x-ray fluorescence results for particulates for three fuels. The presented results are for a typical batch of fuel. The particulate contains about 9%, 32%, and 27% by mass of

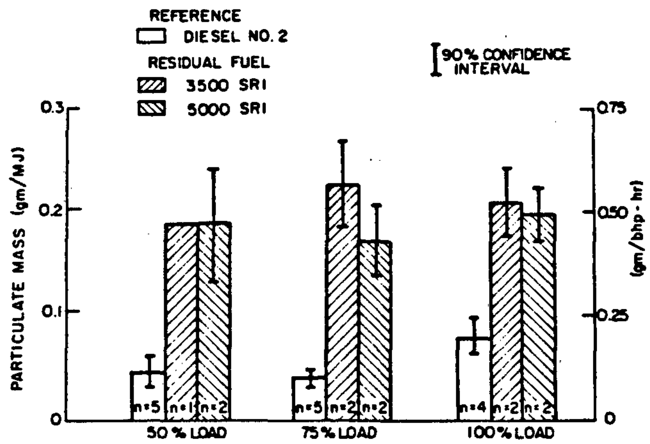

Figure 6: Specific particulate emission (gm/MJ) for three fuels at varying load setting for no water addition; n = number of samples.

TABLE III

ELEMENTAL ANALYSIS OF EXHAUST PARTICULATE MATTER OF TRANSAMERICA DELAVAL'S DSR-46 MEDIUM-SPEED DIESEL (reported in ppm)

Fuel	Diesel No. 2	3500 SRI	5000 SRI	Uncertainty
Aluminum	1500	3000	3200	55%
Silicon	2000	3600	2600	20%
Sulfur	65000	165000	130000	10%
Chlorine	2500	1000	1100	35%
Calcium	17000	115000	110000	5%
Titanium	600	900	500	40%
Vanadium	1100	11000	6000	5%
Chromium	150	280	270	80%
Iron	700	9000	4500	5%
Nickel	1400	16000	10000	5%
Zinc	550	1200	1100	10%
Lead	200	150	210	5%
Strontium	170	200	210	5%
Total	9%	32%	27%	
Uncertainty	+/-1%	+/-3%	+/-3%	

elements with molecular weights greater than magnesium for diesel No. 2, 3500 SRI, and 5000 SRI fuels, respectively. The percentage ash may be up to twice this value depending on the compounds that the elements are found in. For example, if calcium and sulfur exist in calcium sulfate ($CaSO_4$), the molecular weight is nearly twice that for calcium sulfide (CaS). The amount of carbonaceous material in the particulate was inferred by subtracting out an estimate for the ash containing component (x-ray fluorescence mass of elements plus 50%). Figure 7 shows the same information as Figure 6 with the bars divided into an ash containing component and the remainder which is assumed to be carbonaceous. The particles from the residual fuels contain more than three times as much carbonaceous material as the diesel No. 2 particulates: 0.14 gm/MJ and 0.045 gm/MJ, respectively. Even when taking into account the 10% uncertainty in ash content, the difference in the carbonaceous component between the the two fuel types is significant at the 90% confidence level.

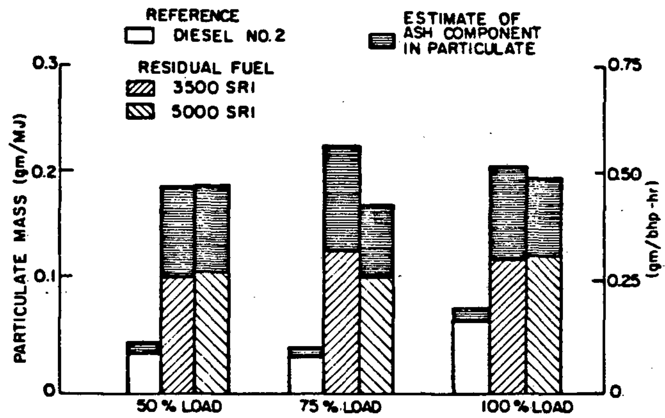

Figure 7: Specific particulate emission (gm/MJ) for three fuels at varying load setting for dry fuels indicating ash containing and carbonaceous components.

Figure 8 shows the particulate levels at 0%, 4%, 8%, and 12% water addition for 3500 SRI fuel; Figure 9 shows the same for 5000 SRI fuel. At all load conditions with 12% water addition, more particulate is emitted than with 0% water addition. Moreover, the fuels containing 12% water formed more particulate than fuel containing 0% or 4% water at both 50% and 75% loads.

Post-test wear and deposit analysis

Engine wear on this DSR-46 engine using water emulsified residual fuels has been compared with wear sustained on the DMRV-16-4 engine using dry residual fuels. The wear rates for the emulsified fuels tests were nearly the same as the dry fuels for the valve stem, valve guide, piston skirts, piston compression rings, and the connecting rod bearings. However, both rails of the oil ring were severely jagged and worn. During the 1000 hour test, the DSR-46 engine with water addition had an average liner wear of 0.046 mm compared to dry residual fuels with 0.008 mm wear. Upon visual inspection, the DSR-46 liners did not show signs of scuffing indicated by metal transfer or scoring. However, the cross-hatch grinding marks from the original surface finish were almost entirely removed.

The emulsified fuels tests gave higher deposits in the combustion chamber, intake and exhaust ports than that seen in the DMRV-16-4 using dry fuels. The hard ash coating on the combustion chamber face was about 0.75 mm thick. The ash on the port surfaces was easily cleaned off. A light, easily removable coating was also found on the turbocharger. Although no ring sticking was experienced on the emulsified fuels, the piston ring faces showed indications of blowby; and

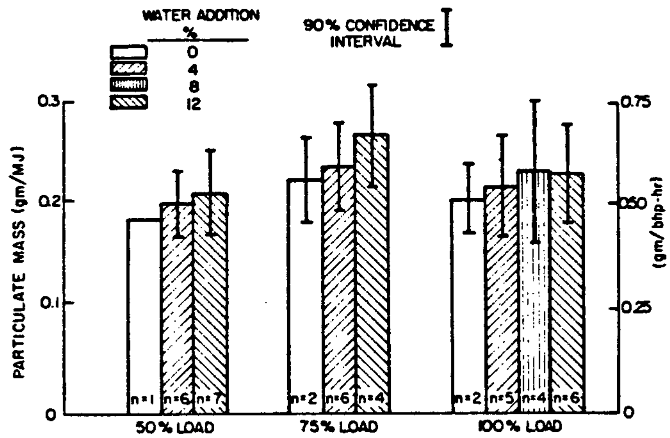

Figure 8: Specific particulate emission (gm/MJ) at three load settings for varying levels of water addition (mean values averaged over all water droplet diameters); 3500 SRI fuel, n = number of samples.

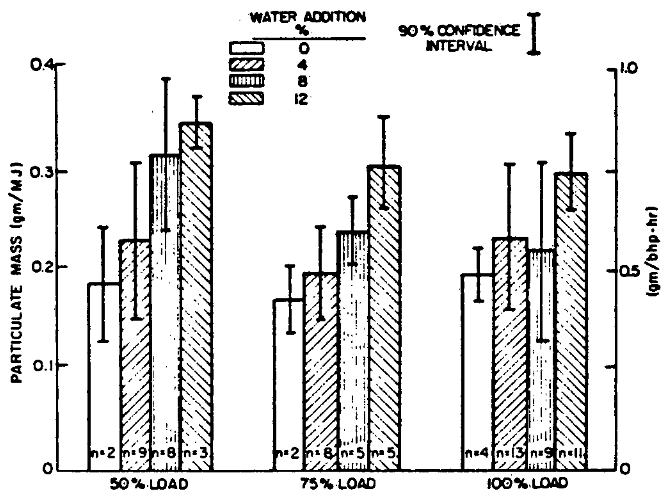

Figure 9: Specific particulate emission (gm/MJ) at three load settings for varying levels of water addition (mean values averaged over all water droplet diameters); 5000 SRI fuel, n = number of samples.

deposit buildup was present in the ring belt area. The cylinder liner area above ring travel was inspected for varnish buildup after testing with each fuel. A light varnish was observed at each inspection with the borescope. (The borescope is inserted in the head with the injector removed.)

The injector nozzle assemblies and fuel injection pumps were inspected by the manufacturer, Bendix Corp. The complete report is found in reference 12. Bendix found signs of rusting and varnish in the nozzle valve area. The injection pump showed the same rusting and varnish phenomena in addition to plunger and barrel scoring. Both the nozzle assemblies and injection pump had water globules present upon disassembly even though a minimum one hour flush with No. 2 diesel was completed before any shutdowns.

DISCUSSION

Nitrogen oxides and thermal efficiency

NO_x was reduced by about 10-15% at 12% water addition. This agrees with several similar studies as summarized by Wilson, et al. (4). In these previous studies, however, more dramatic drops in NO_x concentration were observed as the water to fuel ratio was increased further. Thermal efficiency increases of up to 2% at 12% water addition have been reported (4). But, as depicted in figures 3 and 4, the present work shows a decrease in thermal efficiency of up to 2%. The thermal efficiency and NO_x reductions may be a result of the increasing injection duration with increasing water to fuel ratio. The standard injection equipment on the engine gave a constant water plus fuel injection rate, not a constant fuel injection rate. With increasing water addition the volume of fluid injected increases and hence the injection duration increases. Unfortunately, the equipment required to change the injection rate was not available in time to be used in this program.

Particulates

Ultrachem Corp. (13) has taken particulate samples of a Transamerica Delaval DSRV-16-4 engine which is of the same family as the DSR-46 engine used in the present work. The data from both analyses on diesel No. 2 fuel are in excellent agreement as seen in Figure 10. The Ultrachem data reported is an average value for several measurements. Both analyses show that particulate loading is maximum at 100% load and minimum at 75% load.

Hare and Bradow (14) reported results for heavy-duty, high-speed diesels operating on diesel No. 2 fuel. The two-stroke and four-stroke engines emitted approximately 0.65 and 0.4 gm/MJ (1.75 and 1.0 gm/bhp-hr) particulate, respectively. This is in excess of eight times as much as that produced by TDI's medium-speed engine on the comparable distillate fuel. This can be partially explained by the longer residence times in the medium-speed engine allowing for more

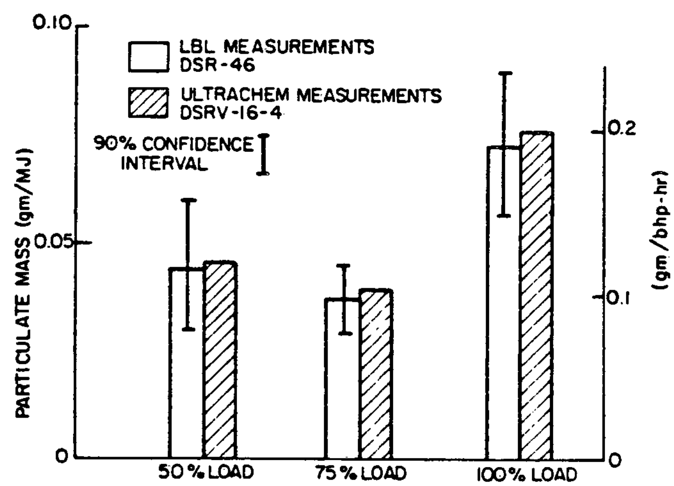

Figure 10: Specific particulate emission (gm/MJ) - Comparison of LBL and Ultrachem measurements with diesel No. 2 fuel.

complete soot particle burnout.

Other researchers (3-7,15) have observed significant advantages when using water addition in compression ignition engines. Sizable reductions in both particulate and NO_x emissions have been reported. However, the bulk of these data were collected at much higher water/fuel ratios than those studied here. Greeves, et al. (3) found that at water/fuel ratios less than 20%, smoke levels (indicative of particulate concentration) were higher than with dry fuels in a high-speed, naturally aspirated, automotive type diesel engine. This may corroborate evidence found in this study. But on the other hand, it is tenuous to compare results obtained in the automotive type engine with the medium-speed engine. Other researchers (4,7) have found smoke reductions with water/fuel ratios of around 50% in medium speed diesels. These soot reductions over dry fuels were more evident at part load conditions. Such high water/fuel ratios were not investigated in this program.

A large portion of the particulate matter is comprised of ash as indicated in Table III. This is much higher than Gabele and coworkers (16) found using two automotive type diesels. They found that using three distillate fuels with slightly different properties and with one highly refined shale derived fuel that the particulate contained less than 2% ash compared with nearly 40% ash with residual fuels. There are two reasons to account for this discrepancy. First, automotive diesels generally burn higher quality fuels than medium-speed engines. Of course the residual fuels will contain much higher levels of metals than distillate fuels. For example, data on fuel sulfur is readily available showing anywhere from two to ten times as much sulfur in the residual fuels as the distillate fuels. Secondly, because of the longer residence times in the larger engine, the extent of soot particle oxidation will be increased. Further, the longer time allows for increased adsorption of other species onto the particle's surface. This is substantiated by information available on the two types of diesel engines. By calculation from data presented in Gabele's paper (16), the amount of soot formed is about 0.006 kg soot/kg fuel burned. Whereas with residual fuels, the medium-speed diesel has a lower value of 0.003 kg soot/kg fuel burned. But, by comparing fuel sulfur to that found on filters shows 0.015 kg S in soot/kg S in fuel in Gabele's study[4] and 0.07 kg S in soot/kg S in the residual fuel in the present study. Even though the uncertainty in these data may be 50% or more, they indicate that a larger fraction of the fuel sulfur in the medium-speed engine is found on the particulate and that this larger engine produces less particulate per unit mass of fuel burned.

<u>Wear and deposit analysis</u>

The wear and deposit results in the engine with emulsified fuels was satisfactory except for the following areas:

(1) Cylinder liner wear with associated blowby.

(2) Fuel injection equipment durability.

These problem areas should be alleviated with minor modifications as discussed below.

The cylinder liner wear, ring belt deposits, high blowby, and excessively worn oil scraper ring are all related (17). As the liner becomes polished from the crown land deposits, the cross-hatch marks are worn away. This smoother surface is unable to hold the lubricant on the walls and the compression ring sealing diminishes increasing blowby. Also, the oil scraper ringewears more quickly because of the insufficient oil film protection on the cylinder walls. Several things could explain the higher crown land deposits: high ash content fuel oil or insufficient water stability of the lubricating oil. The fuel oil did contain greater than 1% ash. Ash can be very abrasive to metal surfaces. A comparison with the dry residual fuel tested in the DMRV-16-4 cannot be made because the fuel's ash content was not measured. Because of the water emulsification, it is likely that water dilution of the lubricating oil was higher than with dry fuels. The additional water in the oil could have a deleterious effect on the oil's additive package. Thus, the lubricating oil additive package must be carefully chosen for this use. No lubricating oil analysis was made to test this hypothesis. The oil used for this test had been previously used for 1000 hours. Therefore, the additive package was somewhat depleted. The lubricating oil becomes less effective at preventing deposit buildup as the piston temperature increases. One would expect lower piston temperatures with water addition because of the water's latent heat of vaporization. But in these series of tests, the water addition is accompanied with an increase in injection duration. This will give a longer combustion duration for heat transfer to the piston. No piston temperatures were measured to determine which of these competing effects dominates. However, from measured cylinder wall temperatures (indicative of piston temperatures), the dry and emulsified fuel tests gave similar results.

The fuel injection equipment manufacturer found that the equipment was distressed. However, with the following changes Bendix has reported that satisfactory operation on emulsified fuels would be possible:

(1) Selection of materials for system components which will not be prone to rusting.

(2) Development of an improved flushing prodcedure to remove trapped water globules from the system.

<u>CONCLUSIONS</u>

(1) NO_x concentrations drop about 10-15% with addition of 12% water. Thermal efficiency falls off slightly (1.5% or less) with 12% water.

(2) No differences were detected in NO_x concentrations, particulate concentrations, or thermal efficiency as a result of water droplet diameter.

(3) TDI's DSR-46 engine emits about 0.051 gm/MJ (0.14 gm/bhp-hr) particulate on diesel No. 2 fuel and about 0.19 gm/MJ (0.50 gm/bhp-hr) on the two high viscosity residual fuels: 3500 and 5000 SRI. However, the particulate matter from the diesel No. 2 fuel contains about 9% ash compared to 30% in the particulate from the residual fuels. Thus, the carbonaceous material produced by the distillate fuel was about 0.045 gm/MJ (0.12 gm/bhp-hr) and 0.14 gm/MJ (0.36 gm/bhp-hr) for the residual

[4]These data were evaluated from information collected on the Federal Test Procedure driving cycle. Certainly the transients adversely affect the particulate concentrations in the high speed engine's exhaust. However, this analysis is concerned with percentage ash in the particulate not a comparison of total particulate emissions of the two engine types.

fuels.

(4) At 12% water addition a higher particulate loading was observed than at 0% or 4% water addition in the 5000 SRI fuel.

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