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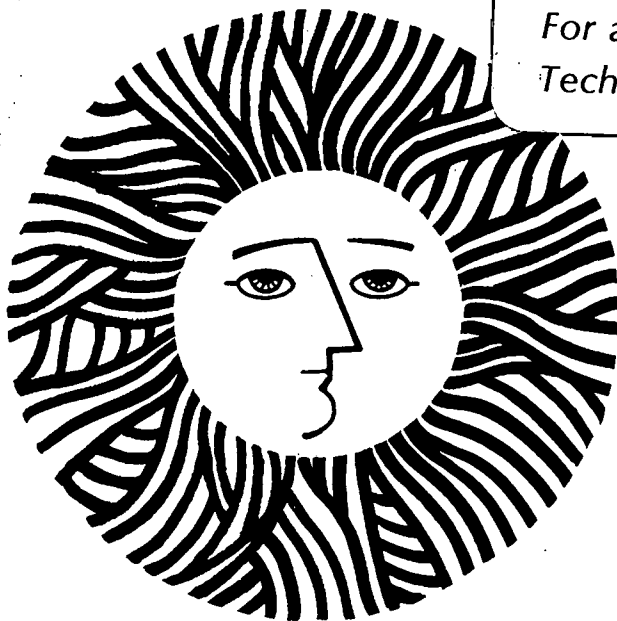
EMISSION CHARACTERISTICS OF A MEDIUM-SPEED DIESEL
USING WATER EMULSIFIED RESIDUAL FUELS

Diana D. Brehob, Frank Robben, Robert F. Sawyer,
and Kenneth R. Pearce

October 1982

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USING WATER EMULSIFIED RESIDUAL FUELS

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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 2% for ther-

mal efficiency (at 12% water). The engine emits about 0.051 gm/MJ (0.14 gm/bhp-hr) particulate for diesel No. 2 and about 0.25 gm/MJ (0.65 gm/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.

INTRODUCTION

Combustion equipment manufacturers and researchers have investigated the potential advantages of water injected into combustion systems since late in the eighteenth 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 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 researchers⁸ 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 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.

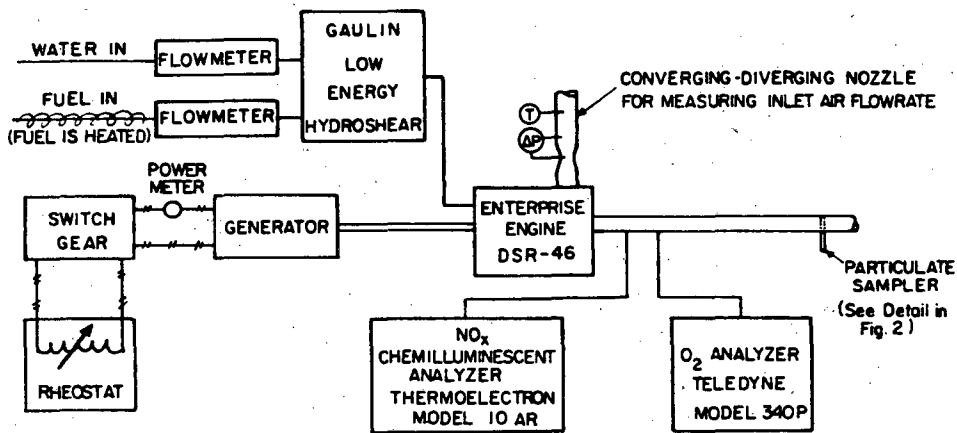
EXPERIMENTAL METHOD

Three residual fuels with viscosities of 1500, 3500, and 5000 Seconds Redwood International* 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

* SRI is nearly the same as Saybolt Universal Seconds.

5000 SRI fuels have been reported. Except for diesel No. 2 which is sufficiently pumpable, all the fuels were heated (up to 110°C for 5000 SRI fuel) 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. The DSR-46, manufactured by TDI is a 1.55 MPa (225 psi) bmp, medium-speed (450 rpm) diesel engine. This engine line is found in marine and stationary power generation applications. Figure 1 schematically show the equipment used in this program: generator, exhaust emissions analyzers, particulate sampler, emulsor, etc.



XBL 829-648

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

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 the 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.

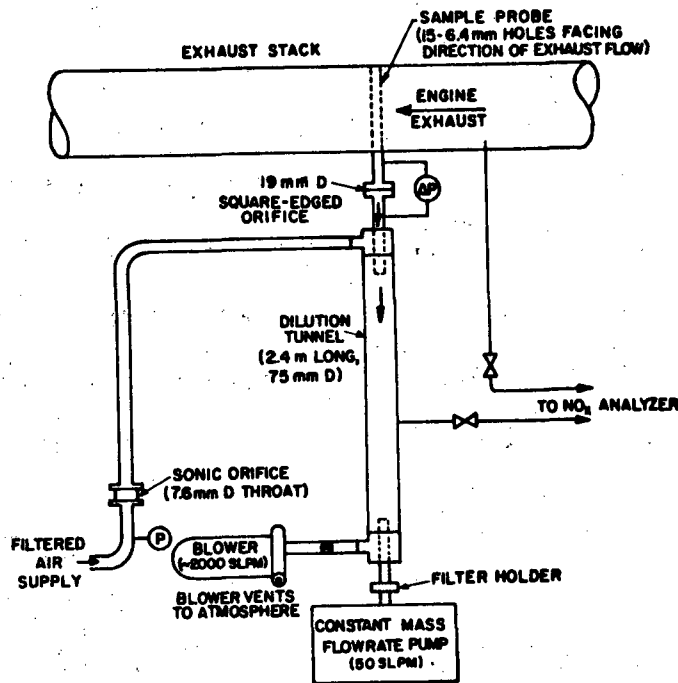
The emulsor unit used in this study was manufactured by the Gaulin Corporation. This prototype, called the Low Energy Hydroshear, can provide water flowrates up to 630 cc/sec (10 gal/min) with a pressure drop of 1.9 MPa (280 psig) for 2-5 micrometer diameter droplets and a 70 kPa (10 psig) drop for producing 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:

$$\text{NO}_x \text{ (corrected)} = 5.9 \times \text{NO}_x \text{ (as read)} / (20.9 - \% \text{ O}_2 \text{ (as read)}).$$

Exhaust O₂ concentration was measured by a Teledyne O₂ 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



XBL 624-5512

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 a chemilluminant analyzer. It was assumed that none of the NO_x decomposed to N_2 and O_2 . Upon dilution, the temperature was lowered sufficiently to prevent reaction toward chemical equilibrium.

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 2.5 cm of water pressure 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 gauge¹¹ operates by measuring the

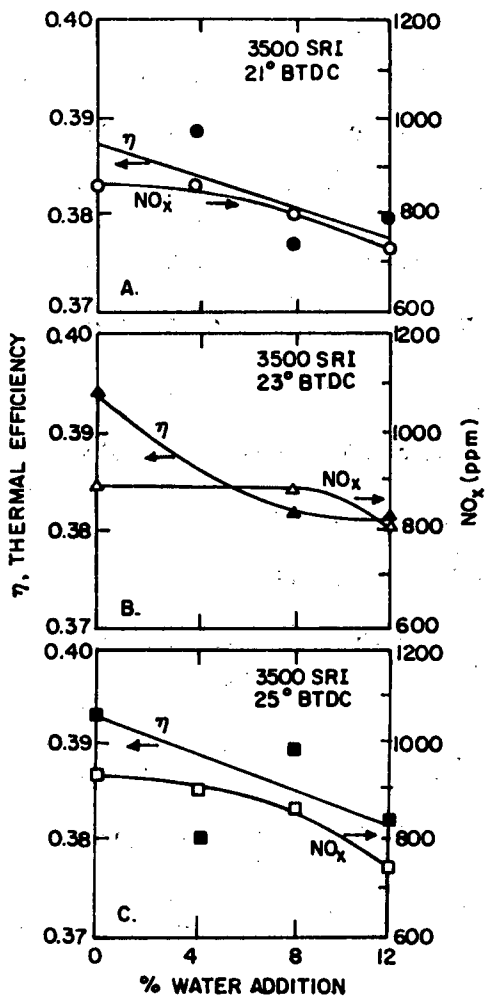
attenuation of beta particles caused by the filter substrate and the particles collected on the filter. The filter is placed between a radioactive source, namely ^{147}Pm , and a detector. The difference in attenuation before and after particle collection yields mass. The precision of this instrument is ± 5 micrograms/cm² with a maximum loading of about 200 micrograms/cm². Actually the precision is ± 3 micrograms/cm² per individual measurement. But, both a tare and final measurement are required. This results in a ± 5 micrograms/cm² total uncertainty. Careful measurements with a microbalance can give slightly better precision. 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.

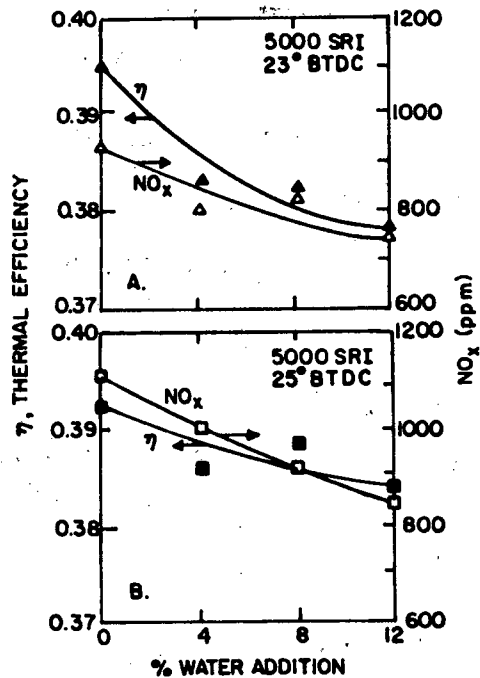
The elemental composition of the particulates was measured by x-ray fluorescence. Each filter was scanned for concentration of 30 elements with molecular weights greater than magnesium. In addition, the diesel No. 2 and 5000 SRI fuels were analyzed by a mass spectrometer for metals content.

RESULTS

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: 2% 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.



XBL 829-6483



XBL 829-6482

Figure 3. NO_x and thermal efficiency response to water addition with 5000 SRI fuel at two injection timings.

Figure 4. NO_x and thermal efficiency response to water addition with 3500 SRI fuel at three injection timings.

The chemilluminiscent 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 show the expected trend: thermal efficiency increases with advanced timing.

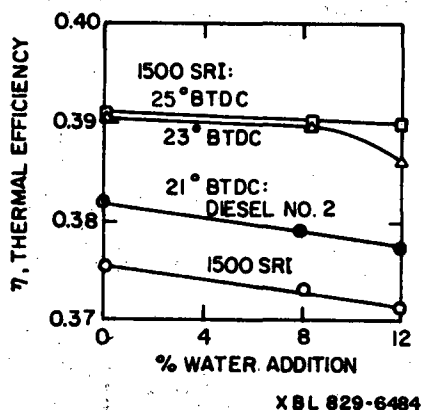


Figure 5. Thermal efficiency response to water addition with two fuels at varying injection timings.

Complete NO_x and thermal efficiency results have been reported by Delaval¹⁶. However, neither NO_x nor thermal efficiency for 50% or 75% loads are presented here. The injector 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.

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.

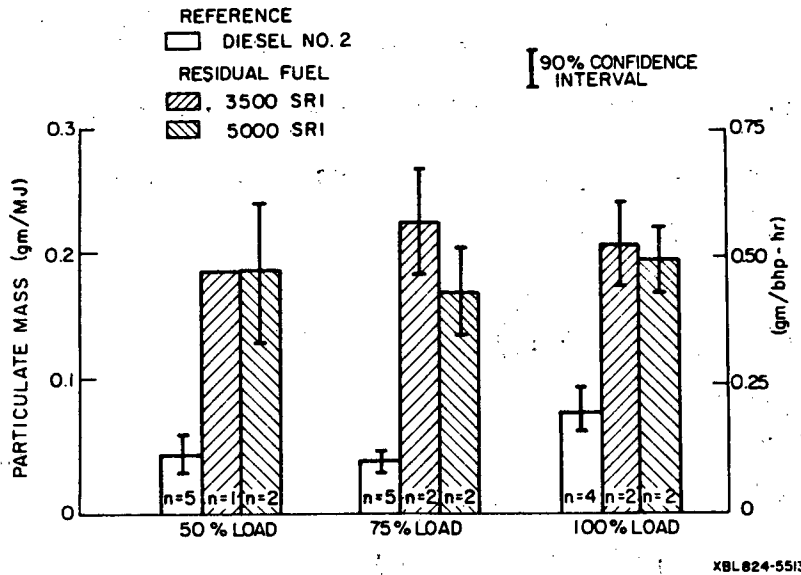


Figure 6. Specific particulate emission (gm/MJ) for three fuels at varying load settings for no water addition: n = number of samples.

* Each bar in Figures 6 and 8-10 represents the average of all samples taken at each point. The vertical line through the bar indicate 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.

Table III contains 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 elements with molecular weight 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 compound that these elements exist in. For example, if calcium and sulfur are found to exist in calcium sulfate, the mass of the calcium sulfate (CaSO_4) is nearly twice that of calcium sulfide (CaS). The amount of carbonaceous material in the particulate was inferred by subtracting out the estimate of 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.

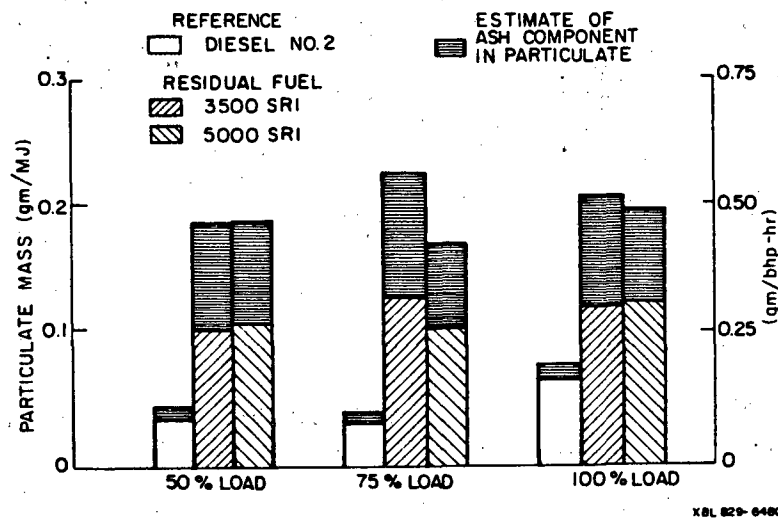


Figure 7. Specific particulate emission (gm/MJ) for three fuels at varying load settings for dry fuels indicating ash containing and carbonaceous components.

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 fuel containing 12% water formed more particulate than fuel containing 0% or 4% water at both 50% and 75% loads.

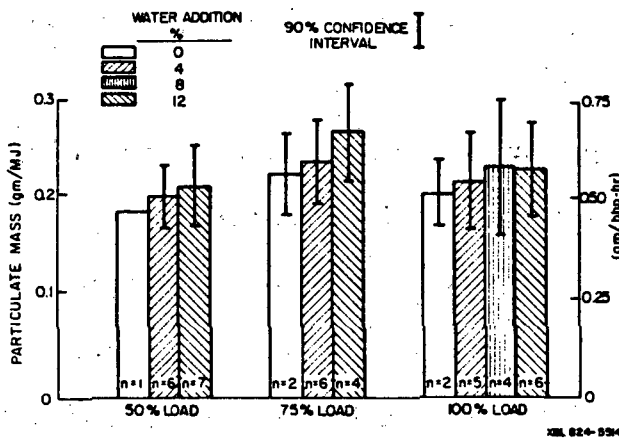


Figure 8. Specific particulate emission (gm/MJ) at three load settings for varying levels of water addition (mean values averaged over all water droplet diameters); 3500 SRI fuel, n = number of samples.

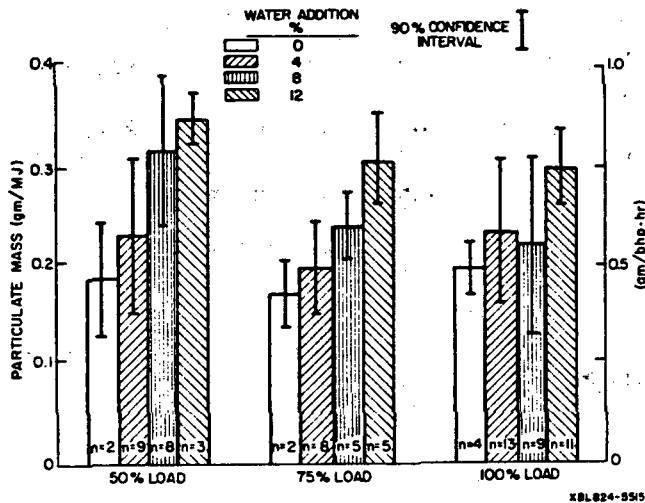


Figure 9. Specific particulate emission (gm/MJ) at three load settings for varying levels of water addition (mean values averaged over all water droplet diameters); 5000 SRI fuel, n = number of samples.

DISCUSSION

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 further increased. 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.

Ultrachem Corp.¹² 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 the maximum at 100% load and the minimum at 75% load.

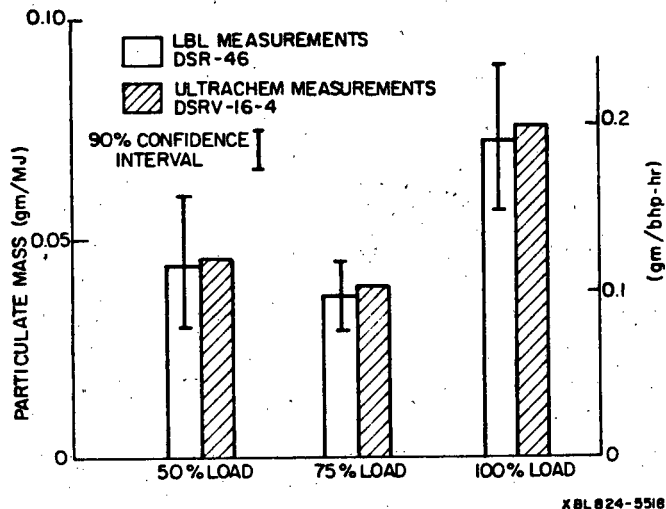


Figure 10. Specific particulate emission (gm/MJ)--Comparison of LBL and Ultrachem measurements with diesel No. 2 fuel.

Hare and Bradow¹³ 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 complete soot particle burnout.

Other researchers^{3-7,14} 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 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 Figure 7. This is much higher than Gabele and coworkers¹⁵ 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% of elements with molecular weight greater than magnesium by mass compared to nearly 30% for the medium-speed engine using 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 contaminants 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,¹⁵ the amount of soot formed is about 0.006 kg soot/kg fuel burned. Whereas,

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 and 0.07 kg S in soot/kg S in fuel in the present study. Even though the uncertainty in these data may be a factor of two, 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. (Gabele's 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 the percentage ash in the particulate, not a comparison of total particulate emissions of the two engine types.)

These tests on the water emulsified fuels did show NO_x reductions as expected. However, the water addition did not decrease particulate emission nor was thermal efficiency increased. Since a somewhat limited range of water addition level and engine operating parameters (fuel injection timing and duration) was evaluated, it is possible that the combination of variables which would meet all the goals was not investigated.

CONCLUSIONS

- 1.) NO_x concentrations drop about 10-15% with addition of 12% water. But, thermal efficiency falls off slightly (2% or less) with 12% water.
- 2.) No differences were detected in NO_x or 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 roughly 9% ash compared to 30% in the particulate from the residual fuels. Taking into account the uncertainty in the ash measurements, the carbonaceous material produced by the distillate fuel was around 0.045 gm/MJ and 0.14 gm/MJ for the residual fuels.
- 4.) At 12% water addition a higher particulate loading was observed than at 0% or 4% water addition in the 5000 SRI fuel.

ACKNOWLEDGEMENTS

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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, CA

MODEL: DSR-46

CYCLE: Four Stroke Diesel

NUMBER OF CYLINDERS: Six

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

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

TABLE III

ELEMENTAL ANALYSIS OF EXHAUST PARTICULATE MATTER OF
TRANSAMERICA DELAVAL'S DSR-46 MEDIUM-SPEED DIESEL
AS DETERMINED BY X-RAY FLUORESCENCE
(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%
Zinc	550	1200	1100	10%
Lead	200	150	210	5%
Strontium	170	200	210	5%
TOTAL	9%	32%	27%	
Uncertainty	+/-1%	+/-3%	+/-3%	

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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