Prevention of Air Pollution from Ships: Diesel Engine Particulate Emission Reduction via Lube-Oil-Consumption Control

Authors: Thomas C. Miller (Lieutenant, USCG), Mark A. Jackson (Lieutenant, USCG), Alan J. Brown (Captain, USN), Dr. Victor W. Wong

ABSTRACT

Strategies to alleviate particulate emissions from diesel engines on board vessels operating in coastal waters are being investigated. The approach is to determine the effectiveness of reducing engine lube-oil consumption as a means to reduce particulate pollutants. In this study, simultaneous lube-oil consumption and particulate emission data were collected on a single cylinder diesel engine for various speeds and loads using three piston-ring and intake-air pressure configurations. A sulfur dioxide-based measurement system was used to measure lube-oil consumption by tracking the sulfur from the lube-oil in the exhaust while using ultra-low sulfur diesel fuel. A scaled down version of a Constant Volume Sampling (CVS) system with a dilution tunnel was used to measure total particulate emission rate. Lube-oil contribution to particulate was determined using chromatography.

The aggregate data show that an average of approximately 64% of the consumed lube-oil ends up as a significant portion of the total particulate. This percentage is lowest at the medium-load conditions at which moderately high exhaust temperatures and lean air-fuel ratios provide an environment suitable for the partial or complete oxidation of the consumed lube-oil. Significant reductions in particulate emission rate could be obtained by controlling engine lube-oil consumption. This can be effected by changes in piston-ring designs (tension and shape, for example) or by manipulating engine operating conditions, such as intake air-pressure, and possibly via other lubrication-system related variables. Replacement of piston rings with low-lube-oil-consumption designs, for example, could be an option with existing engines.

AIR POLLUTION FROM SHIPS

The motivation for this research stems from the maritime community's interest in reducing air pollution from ships, specifically from diesel engines on board ships, sparked by regulatory activities of the U.S. Environmental Protection Agency (U.S. EPA), the California Air Resources Board (CARB), and the International Maritime Organization's (IMO) development of MARPOL Annex VI - "The Prevention of Air Pollution from Ships". The problem of estimating and controlling air pollution from ocean-going ships carrying international cargo is particularly complex. Recent studies [1] show that ship emissions represent more than 14 percent of nitrogen emissions from global fuel combustion sources. The same study also dispelled the notion that ship emissions are always "diluted" away. The current international policy efforts (by IMO) to reduce emissions from ship propulsion systems (NO_x and SO_x) mark the first efforts to define a policy framework addressing these emissions [1]. Diesel emissions contain oxides of nitrogen and sulfur, as well as very fine particulate matter. The control of one pollutant affects the others.

DEFINITION OF THE PROBLEM

Particulate emissions are strongly related to NO_x emissions, and in order to reach extremely low emission levels, reduction of particulate via lube-oil-consumption control is becoming an essential part of the total strategy. Important advances are being made through improvements in the combustion system, including changes such as higher fuel-injection pressures, combustion chamber and piston ring-pack designs, exhaust gas re-circulation and electronic controls, etc. In addition, engine manufacturers and suppliers are actively investigating control of particulate emissions contributed by the engine lubricant. In contrast to other major combustion system changes which are being incorporated in new engines, particulate reduction via lubrication system improvement also offers the potential of application to engines in existing ships. However, much work remains to be done before it can be implemented. This strategy is the focus of this paper.

Studies dating back to the early 1980's have already shown that engine lubricant consumption (hereafter used interchangeably with "lube-oil consumption" or simply "oil consumption") contributes significantly to diesel exhaust particulate emissions. For engines of older vintage, the lube-oil contribution to particulate alone far exceeds the current standard for the total particulate matter for new engines. The lubricant contribution will become increasingly important as the total particulate emission level continues to be reduced in the future. Conclusions in recent reports indicate that it is necessary to further reduce lube-oil consumption to reach mandated diesel particulate emission levels.

The relationship between particulate emissions and lube-oil consumption is believed to vary with the lubricant type, piston ring-pack configurations and operating conditions [3]. However, the detailed mechanisms relating to either parameter are largely unclear. This research attempted to address some of these issues, specifically the piston-ring and operating-condition effects on the correlation between engine lube-oil consumption and diesel-particulate emissions.

The relationship between the diesel particulate emission characteristics - quantity, composition, and lube-oil contribution - and engine lube-oil consumption was investigated. Experiments were conducted on a direct-injection single-cylinder diesel engine in the Sloan Automotive Laboratory at Massachusetts Institute of Technology (MIT). The primary variables measured included instantaneous lube-oil consumption, particulate sample weight, sample composition and instantaneous lube-oil consumption.

TEST BED

A Ricardo Hydra single-cylinder, direct-injection, naturally-aspirated diesel engine purchased from Cussons Technology was utilized as the test bed for this research project. The engine specifics are listed in Table 1.

ENGINE DETAILS: RICARDO HYDRA - SINGLE CYLINDER DI DIESEL		
Type:	Standard DI Hydra	
Bore:	80.26 mm	
Stroke:	88.90 mm	
Number of Cylinders:	1	
Swept Volume:	.4498 liters	
Compression Ratio:	19.8:1	
Aspiration:	Natural	
Rated Speed:	4500 RPM	
Water Out Temperature:	85° C	
Lube-Oil Inlet Temperature:	85° C	
Tappet Clearances:	0.4 mm	
Valve Timing:	IO - 10° BTDC	IC - 41° ABDC
	EO - 58° BBDC	EC - 11° ATDC
Fuel:	Ultra-Low Sulfur Diesel (< 0.1ppm)	
Lube-Oil:	Lubrizol 30W (1.27% sulfur by weight)	

Table 1
Engine Details

LUBE OIL CONSUMPTION MEASUREMENT SYSTEM

A sulfur dioxide-based diagnostic system was fitted to the engine to measure real-time lube-oil consumption (RTOC). An exhaust sample was taken from the engine exhaust manifold. The output voltage, corresponding to the sulfur dioxide level in the exhaust was then converted to lube-oil consumption using the calculations in Reference [4]. Complete descriptions of the RTOC system operation can be found in the theses by Jackson, [6] and, Schofield [7].

Lubrizol 30W lubricating oil was used in the engine during testing. Lubrizol 30W possessed a consistent sulfur content throughout the distillation fractions with good material balance (sulfur recovery). This eliminated the potential for false measurement of the consumption by ensuring that sulfur components did not vaporize disproportionately [8]. Secondly, since it was important to maximize (in comparison with other sources) the sulfur content in the engine lube-oil, Lubrizol 30W with sulfur content ~ 1.27% sulfur by weight was excellent when used in conjunction with the ultra low sulfur fuel. The fuel and lube-oil properties are listed in Tables 2 below.

ULTRA-LOW DIESEL FUEL PROPERTIES	
Sulfur Content (Weight ppm)	0.1

LUBRIZOL 30W PROPERTIES	
Brand	Lubrizol High Sulfur
Type	SAE 30W
Sulfur Content (% by weight)	1.27

Table 2
Diesel Fuel and Lubrizol 30W Properties

SAMPLING PROCEDURES AND ANALYSIS

Particulate Sampling System

Diesel particulate matter is composed of a carbonaceous core comprised of carbon particles formed in the cylinder during combustion. These particles adhere to one another forming agglomerates that form the core of the diesel particulate matter; this fraction is called solids (SOL) [2, 9]. A large fraction of the particulate matter formed in the engine cylinder is oxidized during the combustion process; the remainder leaves the cylinder with the exhaust. Once exhausted to the atmosphere, the exhaust gas is cooled and diluted by ambient air which initiates the adsorption and condensation processes. At this point, some of the many products of incomplete combustion of the diesel fuel and engine lube-oil adsorb onto the carbonaceous material of the particulate. Figure 1, a reproduction from reference [2], displays the particulate formation process.

The intent of the dilution-tunnel sampling system is to simulate release of the exhaust gases to the atmosphere. The exhaust is cooled by ambient air to a temperature of 52° C or less [2], initiating adsorption and condensation, and completing the particulate formation process. Particulate samples are then collected by filtering the dilute exhaust gases.

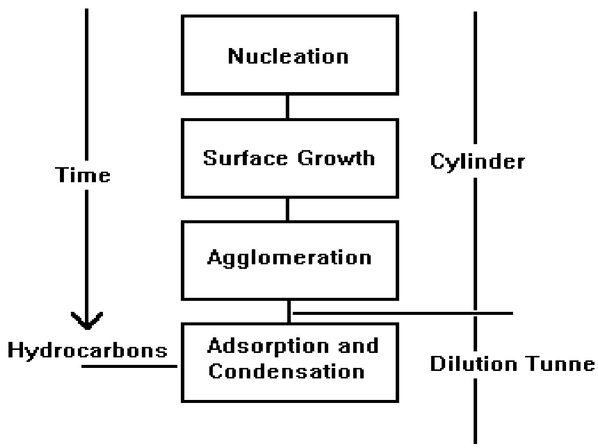

Figure 1
Particulate Formation Process

System Description

A Mini-Dilution Tunnel was constructed by Laurence [3] and used to collect particulate samples. This system was a scaled down version of a Constant Volume Sampling (CVS) Dilution Tunnel constructed in accordance with Environmental Protection Agency (EPA) protocols, similar to the one described by Wong [10]. However, this dilution tunnel was modified to dilute either the entire or a fraction of the exhaust flow.

Particulate samples were collected simultaneously with lube-oil-consumption data during steady state operation of the engine at various speeds, loads, air intake pressures and with various piston-ring configurations. The exhaust was directed into the main stream of the dilution tunnel. Previously, Laurence [3] and Ford [11] had used the dilution air as a means of creating suction, through a venturi, to draw the sample into the dilution tunnel, and as a temperature stabilizer. However, due to the need for a specified flow through the RTOC system, all the exhaust was directed into the dilution tunnel in order to provide sufficient back pressure and generate sufficient flow through the SO_2 RTOC system. Therefore, the dilution air served as a temperature stabilizer for the exhaust stream. The dilution air was filtered to remove lube-oil and moisture from the air (the stated removal effectiveness of the filter is 93% [3]). Concentrations of carbon dioxide were measured in both the raw and diluted exhaust lines to determine the dilution ratio. A sample of the exhaust mixture was drawn through a through a Pallflex Teflon-coated 47mm glass-fiber filter.

Sampling Procedures

Sample times ranged from 5 to 20 minutes, dependent on the operating conditions. Close attention was paid to the sample line temperatures before and after the filter to ensure temperatures were below 52° C [2] throughout the duration of sample collection. Maintaining the filter face temperature below 52° C helped to ensure the proper adsorption and condensation of hydrocarbon on the carbonaceous fraction of the particulate [9]. It had been shown that dilution tunnel temperature has a greater effect on the process of adsorbing hydrocarbons onto solids (producing soluble organic fraction (SOF)) than does the actual hydrocarbon concentration in the tunnel. Also, more consistent data were obtained when the filter face temperatures were held constant [9]. Consequently, dilution tunnel and engine operating conditions were closely monitored and reproduced to obtain the constant filter face temperature between repeated test runs. A diagram of the dilution tunnel is shown below in Figure 2.

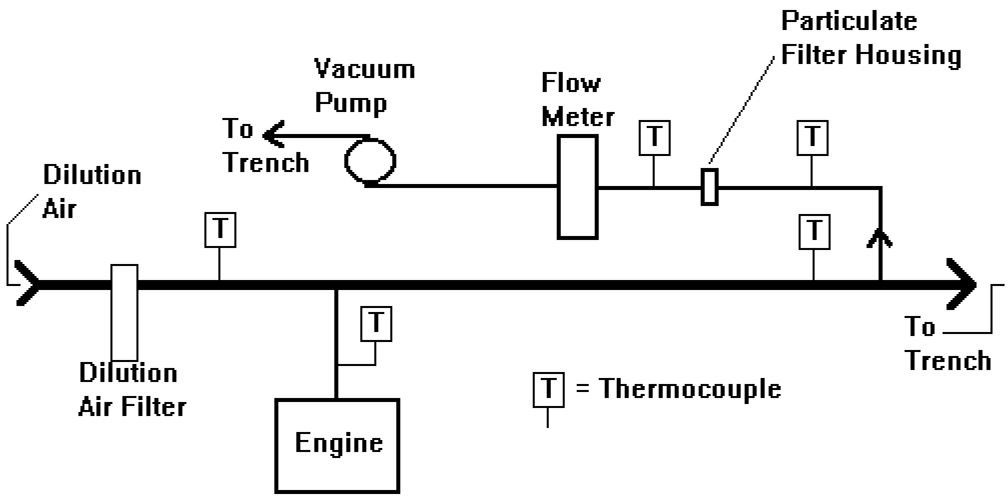

Figure 2
Particulate Sampling System

Sample Analysis

A quantitative analysis was conducted by ORTECH Corporation, a service contractor, on specified samples to determine what percentage of the SOF was derived from the lubricating oil that had been consumed. The fractions of fuel and lubricant in the particulate samples were determined using a ratio of integrated areas (proportional to mass) obtained from chromatograms of three samples: 1) the extracted SOF, 2) the “topped” fuel, and 3) the new lube-oil. The precision of the lubricant derived portion of the SOF results is on the order of 0.001 g/bhp-hr. The data reduction steps for the particulate emission rate, as well as the calculations of the lube-oil consumption rate, are straight forward and are detailed in Reference [4].

Ring Pack Configurations

The standard ring-pack configuration was the standard as set by the manufacturer’s specifications. The first ring, or compression ring, was chrome plated and slightly rounded in shape. The second ring, or scraper ring, was beveled. The third ring, or lube-oil control ring, was chrome plated with two rails and a separate coil spring for tension control. Table 3 displays the ring pack configuration specifications.

RING	DIAMETER (MM)	COLD GAP (MM)	TENSION (NEWTONS)		
			Std Ring Pack	Ring Pack 2	Ring Pack 3
Compression	80.25	0.43	9.3	9.3	9.3
Scraper	80.25	0.43	8.2	8.2	8.2 (Inverted)
Oil Control	80.25	0.51	53.8	28.01	53.8

Table 3
Standard Ring Pack Characteristics

RESULTS AND ANALYSIS

Lube-Oil-Consumption Characteristics

The specific lube-oil-consumption (lube-oil consumption rate per unit engine power output) characteristics for the standard ring-pack configuration are displayed below. The general trends observed are increasing specific lube-oil consumption (OC) with increases in speed at constant load, and decreasing specific OC with increasing load at constant speed, for the 2400 and 3200 RPM operating conditions. Figure 3 displays these trends.

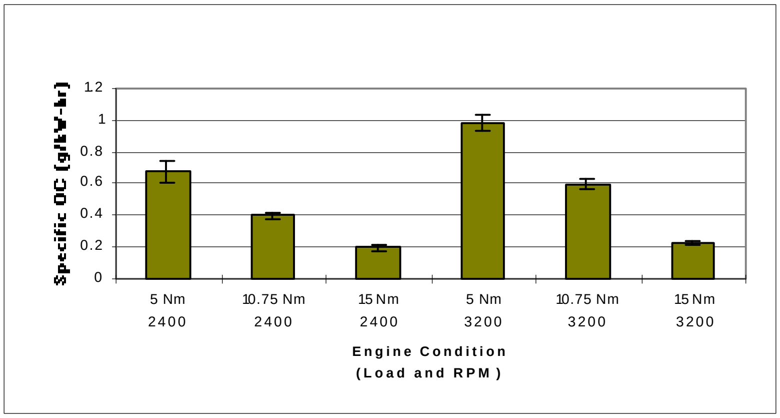

Figure 3
Specific OC Trends for the Standard Ring Pack

Figure 4 displays the specific lube-oil-consumption characteristics for the standard ring pack when the intake-manifold air pressure decreases. Specific OC increases as the air pressure is lowered from 101.3 kPa. The increase occurs as a result of additional lube-oil being drawn into the combustion chamber by the vacuum generated by the drop in air pressure [6].

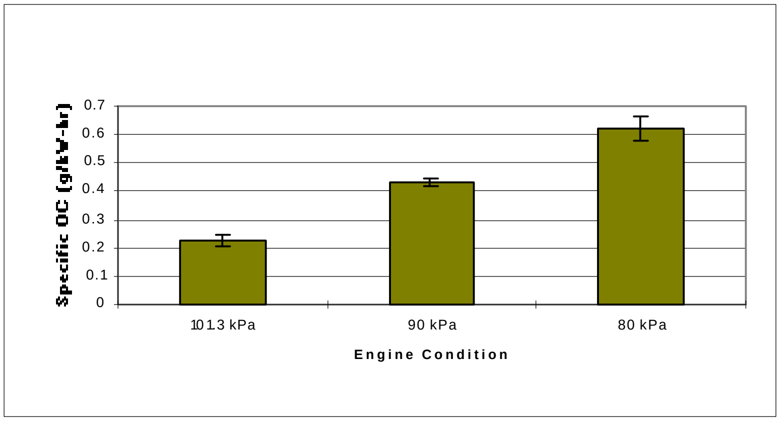

Figure 4
Specific OC Characteristics for Standard Ring Pack; Varied Intake Air Pressures (1200 RPM-Low Load)

Specific OC increases by a factor of ten between the standard ring pack and ring pack 2, and by a factor of 5.5 between ring pack 3. Significant increases were desired to provide a wide range of data points. In each case for the varied ring packs, the specific OC increases with increases in speed, and remains nearly constant for increases in load. See Figure 5.

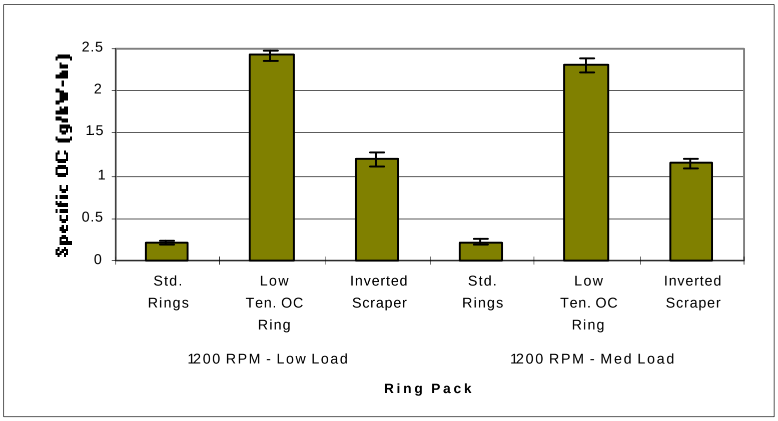

Figure 5
Specific OC Characteristics Comparison Among Ring Packs (1200 RPM-Low & Med Load)

Particulate Characteristics

The breakdown of the specific total particulate rate (TPR) for the standard ring-pack configuration at 2400 and 3200 RPM is displayed in Figure 6. The specific TPR is lowest at medium load, and approximately the same magnitude at low and high loads for each engine speed. The lube-oil-derived soluble organic fraction (SOF) follows the same trend between low and medium loads, but shows little to no increase between medium load and high load.

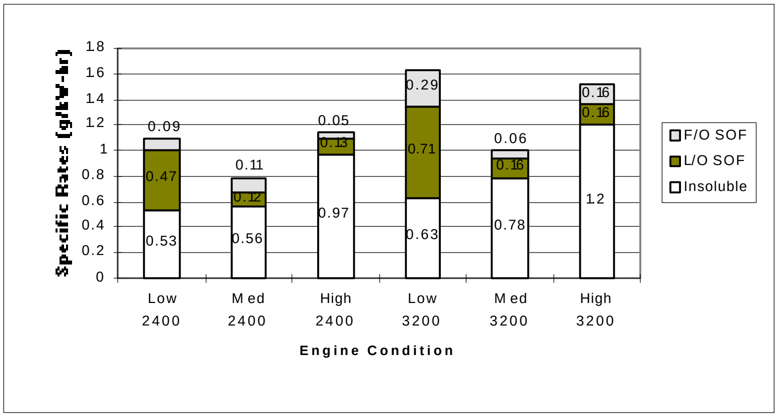

Figure 6
TPR Composition (2400 and 3200 RPM; Varied Loads)

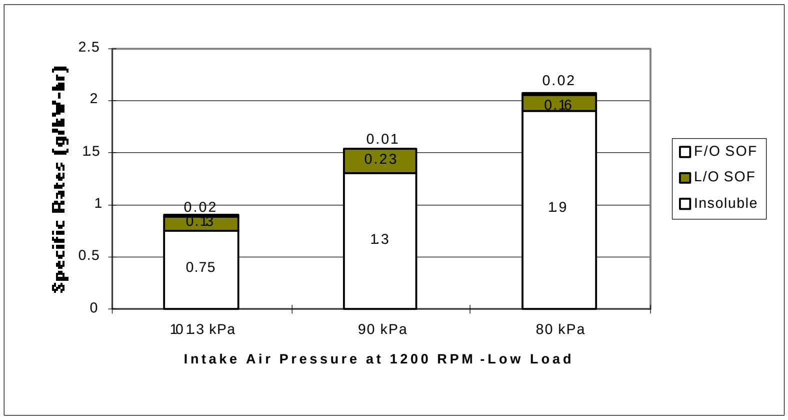

Figure 7
TPR Composition (1200 RPM-Low Load; Varied Intake Air Pressures)

Figure 7 displays the component breakdown for the varied intake air pressures at 1200 RPM-Low Load. The particulate rate increases as the intake air pressure is lowered. Note that the lubricant is the major contributor (over 87%) to SOF at all three conditions. Although only two repeat samples at each air-pressure condition were analyzed for the percentage of SOF contributed by the lube-oil (i.e. L/O SOF as percentage of SOF by mass), the results were very repeatable with standard deviations of 2.9%, 0.7%, 3.2% for the high, medium, and low air-pressure conditions respectively.

Soluble Organic Fraction (SOF)

The generation of the soluble organic fraction (SOF) takes place primarily in the dilution process through adsorption and condensation. The bulk of the SOF is acquired after the exhaust gas is mixed with dilution air [2]. Once the exhaust gases are emitted from the cylinder, cooling from the dilution air initiates the adsorption and condensation processes. Over-fueling, over-leaning, and under-mixing all directly affect the level of hydrocarbons emitted from the cylinder due to incomplete combustion and therefore affect the fuel-derived SOF (F/O SOF). However, only the characteristics of the lube-oil-derived SOF (L/O SOF) are evaluated in this study.

The levels of SOF derived from the lube-oil, for this study, range from 33 to 99 percent of total SOF, indicating that the primary contributor to the SOF was the lube-oil. This suggests that condensation is the dominant process in the development of the SOF. Figure 8 shows that the fraction of the engine lube-oil consumption that contributes to the SOF follows the same general trend as the TPR. The decrease between low and medium loads may indicate that additional lube-oil is being oxidized due to the increase in combustion temperatures which resulted from increased loading. However, this alone does not explain the increase between medium and high load. Oxidation is also a function of the excess air present in the exhaust gases. The air-fuel ratio, and consequently the excess air, is highest at low load and lowest at high load. At low load, there is substantial excess air, but the exhaust temperatures were lower resulting in minimal lube-oil oxidation. Conversely, at high load, the exhaust temperatures were sufficient for oxidation, but the amount of excess air is lower, and therefore oxidation of the lube-oil was again minimal. This trend is observed for both 2400 and 3200 RPM. It is therefore possible that an optimal combination of excess air and exhaust temperature may exist around the medium load condition. Table 4 displays the exhaust temperature and air-fuel ratio behaviors and the resulting effects on the L/O SOF fraction of engine OC, for 2400 and 3200 RPM, as the load is increased.

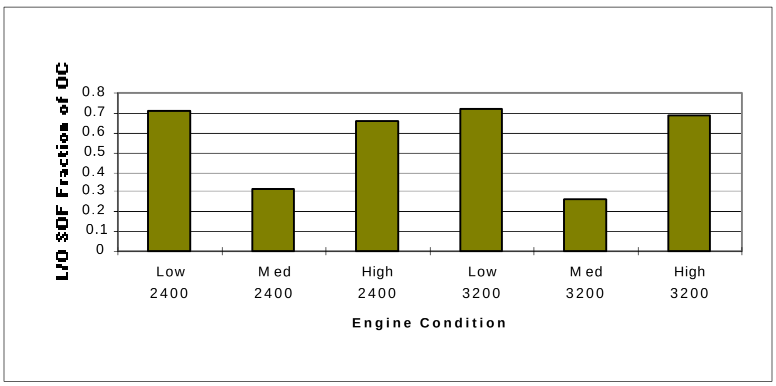

Figure 8
L/O SOF Fraction of Engine Lube-Oil Consumption

TEMPERATURE EFFECT ON DEVELOPMENT OF SOF						
Speed	2400	2400	2400	3200	3200	3200
Load	5 N-m	10.7 N-m	15 N-m	5 N-m	10.7 N-m	15 N-m
Exhaust Temps.	243° C	359° C	468° C	299° C	412° C	580° C
Air-Fuel Ratio	71	52	42	71	50	31
L/O SOF Fraction of OC	.71	.31	.65	.72	.26	.69

Table 4
Temperature & Air-Fuel Ratio Effect on L/O SOF Fraction of OC

Of interest at 1200 RPM, was the behavior of the lube-oil-derived SOF when the intake air pressure is decreased. The specific oil consumption is seen to increase (Figure 4) as intake air pressure decreases from 101.3 kPa to 90 kPa and then to 80 kPa. However, the results depicted in Figure 9 show that the fraction of OC that ends up as L/O SOF actually diminishes. This observed effect appears to be primarily a function of exhaust temperature. As intake air pressure decreases, exhaust temperature usually increases and the measured L/O SOF as a fraction of OC actually decreases. A plausible explanation is that the oxidation or combustion tendency of the consumed lube-oil is higher at the higher exhaust temperatures that are expected at the lower intake air pressure conditions.

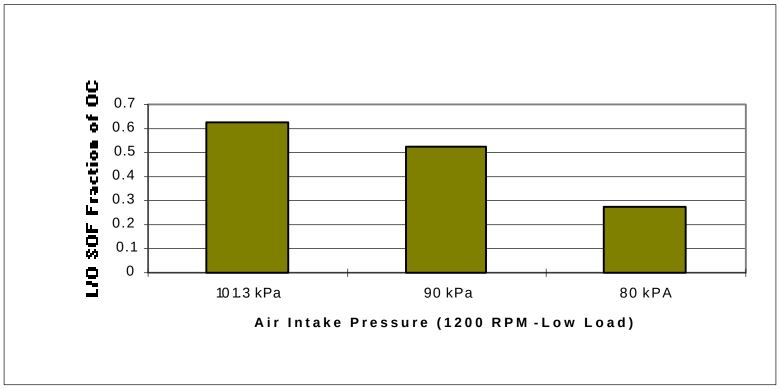

Figure 9
L/O SOF Fraction of Engine Lube-Oil Consumption

L/O SOF Analysis

Previous works [12] indicated that as specific lube-oil consumption increased, the lube-oil-derived portion of the SOF also increased. This trend was consistent with the data obtained for all testing conditions of this study, as shown below in Figure 9 by the data designated as "L/O SOF - Miller", from Miller's thesis [4].

The trend of increasing specific lube-oil-derived SOF with increasing specific OC is evident and appears to maintain a linear relationship. The overall data show a general trend of increasing L/O SOF with increasing OC when a wide range of OC values are considered. It should be noted that while the data in the aggregate did show a general linear trend, there are variations when specific engine speeds or loads are held constant and there are deviations from a straight-line relationship when specific data points are selected. A linear regression, conducted by the method of least squares, fit a curve to the aggregate data displayed below. The slope of the resulting curve is 0.641, and the intercept is zero. As shown in Figure 10, Essig's data [12] displays a survival rate of about 50 percent while the data from this study displays a survival rate of about 64 percent.

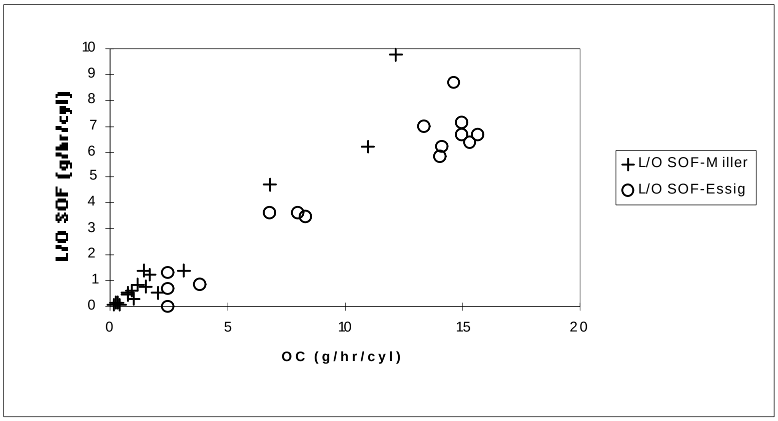

Figure 10
Lube-Oil Derived Soluble Organic Fraction (SOF) vs. Engine Lube-Oil Consumption (OC)

CONCLUSIONS

1. The lube-oil-derived soluble organic fraction (SOF) of the particulate matter increases and decreases with the corresponding change in engine lube-oil consumption. The lube-oil-derived soluble organic fraction is greatest at the high-speed (3200 RPM) - low-load (5 N-m) operating condition. This result agrees with the findings of Essig et al [12]. The agreement with previous work confirms that the dilution tunnel configuration, particulate sampling system, and analysis provide reliable and consistent results.
2. Overall, an approximately linear relationship exists between engine lube-oil consumption and the amount of lube-oil-derived soluble organic fraction - from both previous work and this study. The slope is calculated to be 0.641 for this study, and 0.47 for the data reported by Essig et al [12]. The documented range for the amount of consumed lube-oil contributing to the SOF is between 30 and 80 percent [13]. Therefore, an average value of 64% obtained from this study seems reasonable.
3. The ratio of lube-oil SOF to lube-oil consumption is lowest at the medium-load condition. This may indicate an optimal operating condition for this particular diesel engine. The combination of the exhaust temperature (at least 300° C) and air-fuel ratio (~ 50) at the medium-load condition, for 2400 and 3200 RPM, appears to provide an environment highly suitable for the oxidation of the consumed lubricant. Therefore, the amount of lube-oil contributing to the SOF decreases substantially at this condition.
4. Lube-oil SOF and lubricant consumption (OC) did not behave in exactly the same manner as the intake air pressure was reduced from atmospheric. While OC increased steadily as the intake air pressure decreased, lube-oil SOF first increased between atmospheric pressure and 90 kPa. As intake air pressure further decreased to 80 kPa, lube-oil SOF decreased somewhat. This can be attributed to the increase in the burn-up of lube-oil from the 90 kPa to the 80 kPa condition.

IMPLICATIONS

1. Behavior during transient engine operating conditions can be predicted based on the steady-state results of the particulate formation (specifically the lube-oil-derived SOF). Load transients induce an instantaneous increase in lube-oil consumption corresponding to increases in particulate. This result agrees with practical experience when observing the operation of a diesel engine. As the load on the engine is increased, a temporary plume of particulate is visible from the stack. Once the engine condition stabilizes, the heavy particulate emissions are not as obvious. Additional testing should be conducted to investigate the effects of transient engine operation to validate the conclusion drawn by this study.
2. Significant reductions in particulate could be obtained by reducing the lube-oil consumption. Typically, the SOF contributed between 20 and 90 percent of the total particulate. Of that, between 30 and 80 percent (~ 64% based on curve fit) of the SOF was derived from the lube-oil consumed. This indicates that potential reductions of between 6 and 72 percent of the total particulate generation are achievable by controlling engine lube-oil consumption.

ACKNOWLEDGEMENTS

This paper is the result of research sponsored by the Maritime Administration, under Corporate Agreement Number DTMA91-95-H00051, with support from the United States Coast Guard (USCG). Special thanks to Mr. Daniel W. Leubecker of MARAD and Dr. Alan Bentz of the USCG Research and Development Center for their guidance and support. This research was also supported by the Consortium of Lubrication in Internal Combustion Engines at Massachusetts Institute of Technology, whose members include Dana Corporation, Peugeot, Renault, and Shell Oil Company. The authors would like to thank several people who provided assistance to the completion of this research: Mr. John Lopatynski, ORTECH Corporation, Mr. Norbert Abraham, Sr., Mr. Richard Flaherty, Mr. Gordon Starr, Mr. Weibo Weng, Dr. Dana Richardson, Cummins Engine Company, and Mr. Dave Fiedler, Dana Corporation. This research is part of the U. S. Coast Guard / U. S. Maritime Administration Cooperative Research on Marine Engine Exhaust Emissions.

REFERENCES

1. Corbett, J. J. and Fischback, P., Ship Propulsion Air Emissions: Estimation and Regulation, 1997 Diesel Engine Emissions Reduction Workshop, San Diego, CA 1997.
2. Heywood, J.B., Internal Combustion Engine Fundamentals, McGraw-Hill Book Company, New York, 1988.
3. Laurence, R.B., “The Effect of Lubrication System and Marine Specific Factors on Diesel Engine Emissions,” Masters Thesis, Departments of Ocean and Mechanical Engineering, 1994.
4. MARAD Report MA-ENV-820-96004, “Prevention of Air Pollution from Ships: Characterization and Assessment of Diesel Particulate Emission Reduction via Lube-Oil Consumption Control,” U.S. Department of Transportation, Maritime Administration.
5. Miller, T.C., “Characterization of Lube Oil Derived Diesel Engine Particulate Emission Rate vs. Lube Oil Consumption,” M.S. Thesis, Department of Ocean Engineering and Department of Mechanical Engineering, May 1996.
6. Jackson, M.A., “Assessment of a Sulfur Dioxide-Based Diagnostic System in Characterizing Real Time Oil Consumption in a Diesel Engine,” Masters Thesis, Departments of Ocean and Mechanical Engineering, 1996.
7. Schofield, D.M., “Diesel Engine Instantaneous Oil Consumption Measurements Using the Sulfur Dioxide Tracer Technique,” Masters Thesis, Departments of Ocean and Mechanical Engineering, 1995.
8. Ariga, S., et. al., “Instantaneous Unburned Oil Consumption Measurement in a Diesel Engine Using SO_2 Tracer Technique,” SAE Paper 922196, 1992.
9. Waldenmaier, D.A., et. al., “The Influence of Sampling Conditions on the Repeatability of Diesel Particulate and Vapor Phase Hydrocarbon and PAH Measurements,” SAE Paper 900642, 1990.
10. Wong, V.W., et. al., “Effects of Catalytic Wire-Mesh Traps on the Level and Measurement of Heavy-Duty Diesel Particulate Emissions,” SAE Paper 840172, 1984.
11. Ford, E.J., “The Effects of Lubrication Parameters and Exhaust Aqueous Injection on Diesel Engine Oil Consumption and Emissions,” Masters Thesis, Departments of Ocean and Mechanical Engineering, 1995.
12. Essig, G., et. al., “Diesel Engine Emission Reduction - The Benefits of Low Oil Consumption Design,” SAE Paper 900591, 1990.
13. Farrar, J.R., et. al., “Quantitative Diesel Particulate Analysis using Gas Chromatography/Mass Spectrometry,” Proc. Instn. Mechanical Engineers, Vol 207, 1993.