

Carbon Monoxide Emissions from Marine Outboard Engines

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ABSTRACT

Carbon Monoxide (CO) has become a pressing issue for the recreational marine industry. An increasing number of boating incidents have been linked to CO poisoning caused by emissions from gasoline-powered marine engines. Measurements by the National Institute for Occupational Safety and Health (NIOSH) and the U.S. Coast Guard have confirmed potentially hazardous CO concentrations near many of these engines. The measurements have also shown much lower CO concentrations for Evinrude® two-stroke direct-injected engines.

This paper reviews national and international CO emission regulations for marine engines and discusses CO formation and reduction mechanisms. The differences between homogeneous- and stratified-charge combustion systems on CO formation, resulting from design and calibration criteria, are analyzed. The primary driving factors for CO formation under high-load homogeneous operation are driven by a desire to maximize power output and a necessity to control the thermal loading of internal engine components. Part throttle and low-load operation are largely driven by emissions and run-quality requirements.

Several distinct advantages for direct-injected engines lead to the formation of significantly lower CO concentrations in the exhaust. The unavoidable over-scavenging of air aids in diluting cylinder-out CO levels. This, combined with high exhaust gas temperatures, can generate a significant post-oxidation effect. The post-oxidation effect was investigated in detail and some engine test results are presented. Stratified operation at low loads with high air-fuel ratios result in CO concentrations up to 100 times less than homogeneous-charge engines.

Carbon Monoxide (CO) is a colorless and odorless gas. CO exposure is estimated to be responsible for more fatal unintentional poisonings in the United States than any other agent [1]. CO poisoning occurs when carbon monoxide replaces oxygen in the hemoglobin. Hemoglobin is responsible for delivering life-critical oxygen to cells in the body. The affinity of hemoglobin to CO is estimated to be 200 to 300 times higher than the affinity to oxygen [2]. As a result, CO can accumulate in the blood stream and drastically reduce its capability to carry oxygen to the cells.

CO has become a public issue in recent years after boating-related deaths previously thought to be drownings were linked to CO poisoning. Between 1990 and 2003 over 503 boating-related CO poisonings were reported in 26 states, 101 of the people died, and at least 107 others lost consciousness [3]. Additionally, it is believed that a large number of unexplained drownings could be CO related. For example, on Lake Powell drownings are being carefully investigated for CO linkage, and the gas was found to be a contributor in many of the cases. The actual number of CO poisonings is expected to be much higher than currently known because many minor CO poisonings that do not require medical attention go unreported, and other incidents are never linked to CO as a possible cause.

The reported work on CO emissions from gasoline internal combustion engines can be divided into two main categories—a lower CO production during combustion development and a reduction in CO produced through after-treatment.

Several authors have investigated the effect of oxygen enriched intake air on engine performance. The higher oxygen content substantially reduced CO and hydrocarbon (HC) emissions. The reductions, however,

INTRODUCTION

came at the price of higher emissions of nitrogen oxides (NO_x), resulting from increased combustion temperatures [5-8]. Instead of adding oxygen to the intake air, several authors tested oxygenated fuels for

their effect on emissions. These fuels were found to reduce CO and increase NO_x emissions. Increasing the concentration of oxygenated fuel components produced trends similar to those observed under lean operation [9-13]. Myers et al. investigated the effect of combustion chamber surface temperature on the emissions of a port fuel-injected engine at a wide range of air-fuel ratios and found no significant effect on CO emissions [14]. Poole et al. coated the combustion chamber of a single-cylinder two-stroke engine with a 0.5-mm-thick ceramic layer and were able to substantially reduce CO emissions because of a leaner calibration, which was enabled by more complete combustion [15].

Burrahm et al. showed that air injection into the exhaust, exhaust gas recirculation (EGR), and ignition timing changes had a positive effect on the CO emissions of a small four-stroke generator engine [16]. Crabtree et al. investigated the effect of different catalytic after-treatment strategies on the emissions of a small air-cooled four-stroke engine. The study showed that over 95% of the CO and HC emissions could be oxidized with a two-way catalyst and a thermal reactor system with controlled amounts of exhaust air [17]. Carlson et al. equipped a number of older model year (1975-1980) vehicles with components to upgrade the emissions control system and were able to reduce CO emissions more than 60% from the baseline. However, after 48,000 kilometers, the CO reduction had degraded to only 20% [19]. Khatri et al. compared the idling performance of a three-cylinder passenger car engine with a carburetor and a single point fuel injection system and found that the fuel injection system resulted in lower cylinder-to-cylinder variation in mixture strength and lower levels of CO and HC emissions [20].

This paper reviews existing emissions regulations with respect to CO and presents a comparison of CO emissions from different outboard engine technologies. Formation and reduction mechanisms for CO are also presented and discussed.

CO EMISSIONS REGULATIONS REVIEW

UNITED STATES

Environmental Protection Agency (EPA) regulations for recreational boat propulsion engines and generators were intended to control HC and NO_x emissions rather than CO. The EPA estimates that recreational marine engines contribute the second highest average quantity of HC exhaust emission, only behind that of lawn and garden equipment. (EPA 1996) Under the Clean Air Act, EPA regulations apply specifically to newly sold engines only.

EPA regulations for the recreational boating industry can be divided into three categories:

1. Regulations for outboard spark-ignition marine engines and personal watercraft

2. Regulations for inboard and stern drive engines
3. Regulations for large (> 19 Kw) and small (< 19 Kw) generators

EPA regulations that apply to outboard spark-ignition marine engines and personal watercraft were passed in 1996 under 40 CFR, Part 91. This regulation is currently being phased in (between 1998 and 2006). It is intended to reduce HC and NO_x emissions by a factor of four. Although this regulation is not directed at CO, the current evaluation shows that there are CO benefits. The primary emission reduction technologies under this regulation are replacement of conventional two-stroke engines by direct fuel-injected two-stroke engines or four-stroke engines.

The other class of recreational boat drive engines are the inboard and stern-drive spark-ignition engines. EPA has recently published a notice to regulate inboard and stern-drive marine engines. These engines are often, but not always, larger than outboard engines and have a higher power output. Many have automotive origins. Inboard and stern drive engines potentially could reduce emissions by using a feedback electronic air-fuel control, an electronically controlled exhaust gas recirculation, and a three-way catalytic converter. Southwest Research Institute is currently conducting work in this area for the EPA.

A final class of engines used on recreational boats is the generator type, which is not addressed under Marine engine rules. Rather, they fall under small equipment and large spark-ignition engine rules, depending upon their size. Regulations for large generators, classified as those producing 25-hp or 19-Kw or more, became effective in 2004. These regulations require catalysts to control HC and NO_x and a 95% reduction in CO by 2007. However, most generators on recreational boats are smaller than 19-Kw, and, thus, fall under small equipment rules, which are directed at residential lawn and garden tools. Because environmental rules are primarily concerned with HC pollutants, CO emissions from recreational boats are not currently addressed. Ironically, new, large gasoline-powered generators that produce 5 grams of CO per Kw/hour are regulated in comparison with the non-regulated small gasoline-powered generators, having a mass CO production rate that is 100 times greater (500 grams of CO per Kw/hour). The CO cap, which cannot be exceeded for small equipment, under EPA regulations, is 610 grams of CO per Kw/hr. These differences in CO emission rates between large and small gasoline-powered generators are primarily driven by economic issues and industry concerns, rather than by technological feasibility or health concerns.

EUROPE

European emissions legislation is set forth in the European Commission (EC) regulations. The EC standard uses the International Council of Marine

Industry Associations (ICOMIA) cycle and regulates HC, NO_x and CO, implementing the standard in two stages. EC-1 has separate limits for two-stroke and four-stroke engines, specifying higher HC and lower NO_x and CO limits for the two-stroke engines, as shown in Table 1. EC-2, which goes into effect in 2008, is independent of engine technology.

	EC-1 4ST	EC-1 2ST	EC-2
	2006	2007	2008
Area	Europe (EC)	Europe (EC)	Europe (EC)
HC g/kWh	7.2 - 17	32 - 36	5.2 - 15
NO _x g/kWh	15	10	15
CO g/kWh	154 - 231	153 - 163	69 - 221

Table 1: European Commission emissions limits for marine outboard engines.

Within the European Union, the regulatory agency for the Bodensee has developed its own, much more stringent emissions limits, similar to the California Air Resources Board (CARB) in the United States. Table 2 shows the emissions limits for the Bodensee. The BSO-1 standard was used as the basis for the EC-2 limits. The only engines currently meeting the BSO-2 standard are inboard diesel engines and gasoline Multi-Port Fuel Injection (MPFI) engines with catalytic converters.

	BSO-1 Bodensee	BSO-2 Bodensee
	1995	1997
Area	Lakes of GER, A and SW	Lakes of GER, A and SW
HC g/kWh	5.2 - 15	1.8 - 8.2
NO _x g/kWh	15	5.2 - 7.4
CO g/kWh	69 - 221	24 - 109

Table 2: Bodensee local authority emissions limits.

The CO limits set forth in the European regulations are a function of power output and are generally higher for lower power engines. Figure 1 shows the CO limits as a function of engine power output for the EC-1, BSO-1, and BSO-2 standards. The graph also shows CO emissions for various clean technologies (2-stroke, direct injection; 4-stroke carbureted, and 4-stroke electronic fuel injection) based on Model Year 2004 EPA data. The figure illustrates that carbureted four-stroke engines produce very high CO concentrations at lower engine power outputs. The EC-1 standard is met by 94% of direct-injected two-stroke engines, but only by around 18% of fuel-injected four-stroke engines. The only

technology currently meeting the more stringent BSO-1 CO standard is the two-stroke direct-injection.

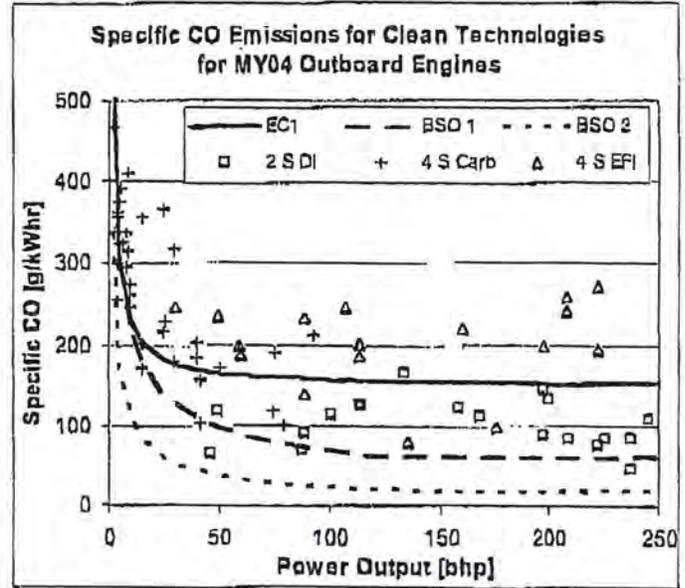


Figure 1: European CO limits and outboard engine CO emissions by technology (MY2004 EPA data)

CANADA

Environment Canada will adopt EPA-1 regulations in the year 2007, which currently does not include any CO limits.

CO EMISSIONS DATA

In a study performed under an interagency agreement between NIOSH and the United States Coast Guard, approximately 25 recreational boats of varying ages were evaluated for their risk of CO exposure. The data showed that CO concentrations and exposures were highest in the vicinity of the engine exhaust and generally decreased with increasing boat speed [33]. These data indicate that the exhaust CO concentration at low to medium engine speeds plays an important role in minimizing exposure and reducing the risk of carbon monoxide poisoning.

The following compares CO emissions data for current clean outboard engine technologies. Evaluated engines meet the California Air Resources Board 3-Star emissions limits for 2008. The data were independently generated according to the ICOMIA cycle in accordance with EPA certification test procedures. Figure 2 shows a comparison of exhaust CO concentrations for the ICOMIA cycle, for different technologies and power outputs. The graphs display the emission levels of the DI two-stroke engine relative to the four-stroke engine. The data illustrate that DI two-stroke engines produce significantly lower CO levels. The difference increases towards lower engine speeds.

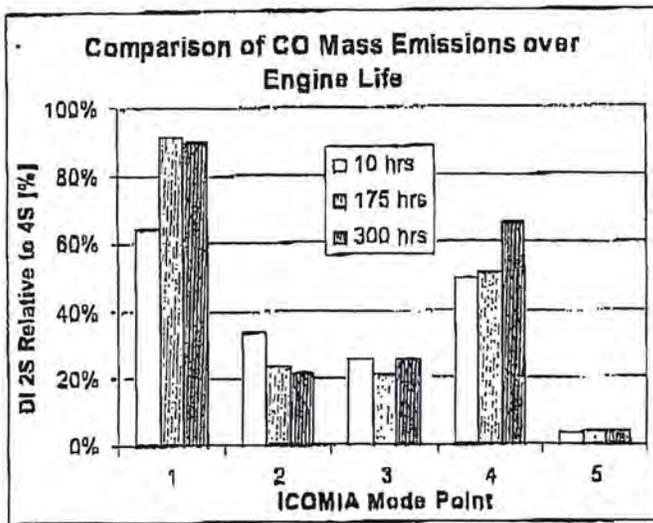


Figure 2: Reduction of CO mass emissions from 4S to DI 2S technology.

Figure 3 shows the reduction of CO concentrations from four-stroke to two-stroke DI technology for the ICOMIA cycle. Emissions were monitored over the useful life of two current technology 90-hp outboard engines and results for 10, 175, and 300 hrs are presented. The graph illustrates that CO emissions are significantly lower for the DI two-stroke engine at all mode points, with the least difference at mode 1 (Wide Open Throttle) and the largest difference at mode 5 (Idle).

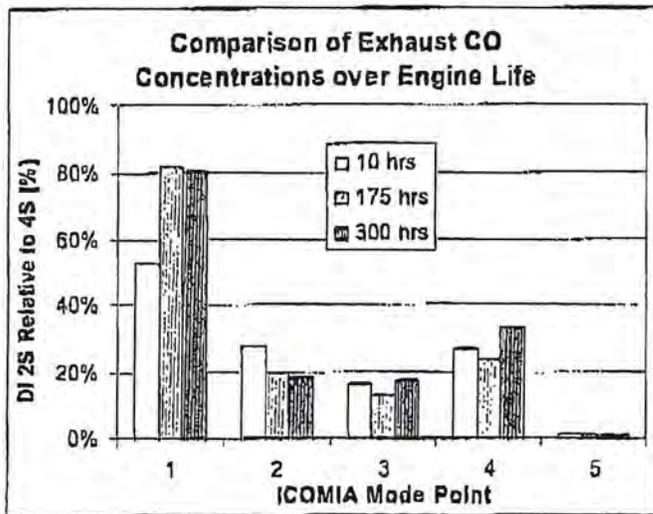


Figure 3: Reduction of exhaust CO concentrations from 4S to DI 2S technology.

Figure 4 shows the CO concentrations in the exhaust as a function of the specific CO emissions for the same two engines, using the data from modes 1 thru 4 (specific emissions data cannot be calculated for mode 5 because it is an idle condition). The data demonstrate that there is a clear correlation between specific CO emissions and CO concentration and, thus, exposure risk. The data for the DI two-stroke engine deviate from the linear

relationship due to the effect of the excess oxygen in the exhaust, especially under stratified operation. A similar clear correlation between CO mass emissions and concentration at idle are shown in Figure 5.

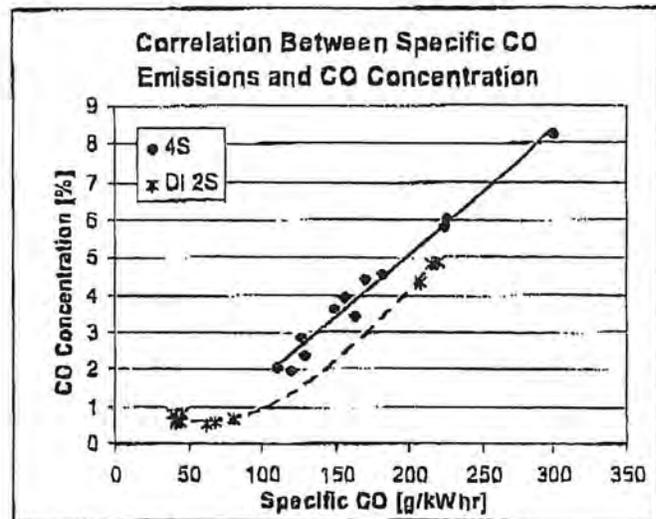


Figure 4: Specific CO emissions and CO concentration

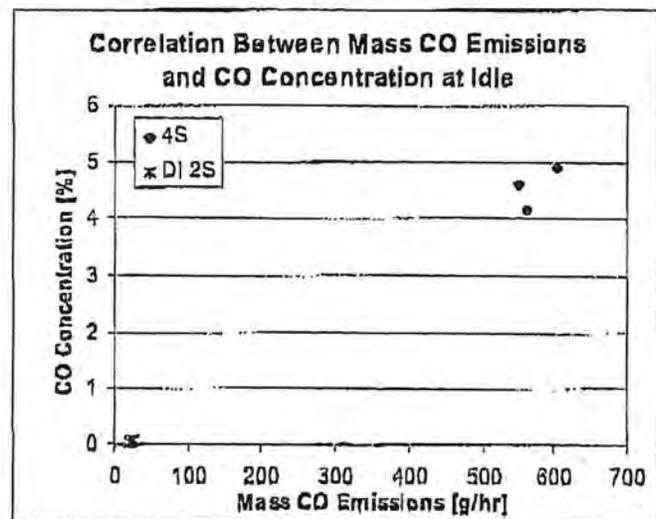


Figure 5: Mass CO emissions and CO concentration at idle.

Figure 6 shows a comparison of CO concentrations during an engine cold start for the two different technologies. It is apparent that transient effects are negligible for the direct injected engine and that steady state levels are approximately 90 times lower than for the four-stroke engine.

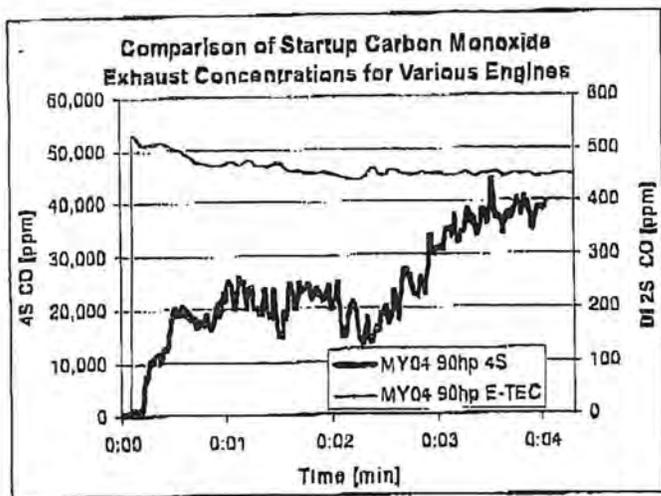


Figure 6: Startup CO emissions for two outboard engine technologies.

The data show that the direct injected two-stroke engine produces significantly lower CO emissions, both in terms of mass or specific emissions and concentrations levels. The difference between the technologies is largest at idle and low engine speeds where the risk of CO exposure is considered to be highest.

CO FORMATION

CO is formed as a result of incomplete combustion of carbon atoms due to lack of oxygen. S. R. Turns characterized the oxidation of higher paraffin in the form C_nH_{2n+2} ($n > 2$) as a three-step process [31]:

1. Breakdown of the fuel molecule by O and H atoms and formation of olefins and hydrogen. The hydrogen oxidizes to water.
2. Unsaturated olefins oxidize to CO and H_2 . All of the H_2 is oxidized.
3. The CO oxidizes via $CO + OH \rightarrow CO_2 + H$.

The less oxygen that is left after the first two steps results in more CO remaining unoxidized in the third step.

Figure 7 shows general trends for the emissions concentration as a function of air-fuel ratio for homogeneously operated four-stroke engines. The graph clearly illustrates that CO concentrations increase rapidly with a decrease in available oxygen (air-fuel ratios lower than stoichiometric). HC concentrations follow a similar trend although at a rate and level that is three orders of magnitude lower. At the same time, NO_x concentrations decrease with decreasing air-fuel ratio at a rate that is approximately 30 times higher than that of HC increase. Hence, in light of the much larger contribution of NO_x compared with HC and regulations that limit only the sum of $HC+NO_x$ and not CO, this relationship clearly presents a tradeoff. It is biased towards the reduction of NO_x by

reducing the air-fuel ratio at the cost of increased CO emissions.

Other reasons for a rich calibration at Wide Open Throttle (WOT) include possible power gains, as illustrated by the curve labeled "M" in Figure 7 and reduced knock tendencies from the lower combustion temperatures.

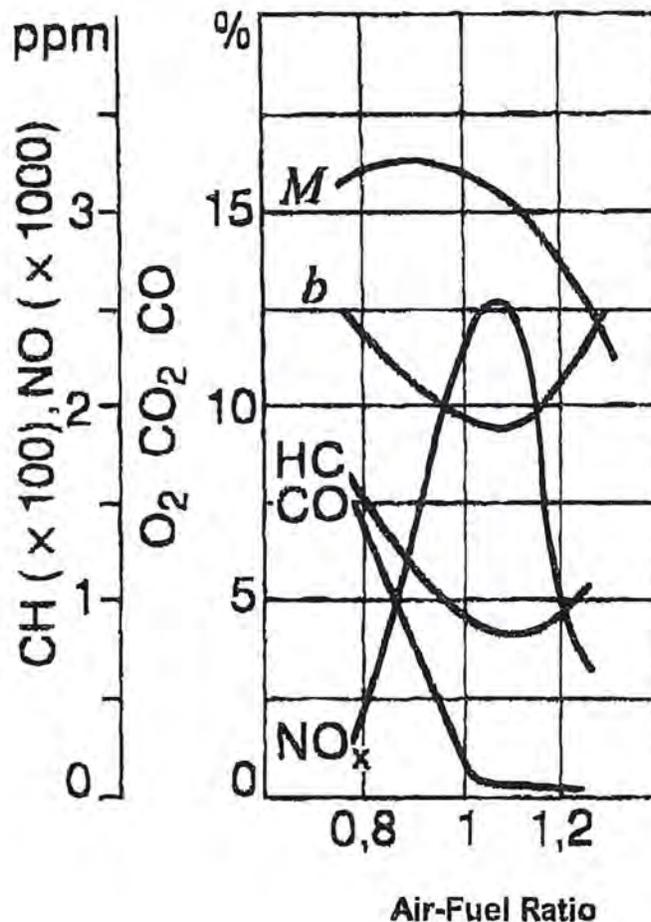


Figure 7: Influence of air-fuel ratio (relative to stoichiometric air-fuel ratio) on exhaust emissions concentrations [29] ("M" is torque and "b" is specific fuel consumption.)

The trends shown in Figure 7 are representative of homogeneously operated four-stroke engines. Although DI two-stroke engines are quite different, the dependence of CO formation on air-fuel ratio should be at least comparable for local combustion zones. This general trend is confirmed by the data in Figure 8, showing results from the ICOMIA test points. However, NO_x concentrations are generally much lower due to the lower effective compression ratio and internal exhaust gas recirculation and, thus, the calibration tradeoff between high CO and low NO_x does not apply. Additionally, DI two-stroke engines have varying levels of excess oxygen resulting from the unavoidable short-circuiting of fresh charge during scavenging. Despite a possibly rich combustion, the excess oxygen present in

the exhaust gas can be oxidized by some of the remaining CO when the emissions are sufficiently mixed and temperatures high enough, as will be shown in the section on Post Oxidation.

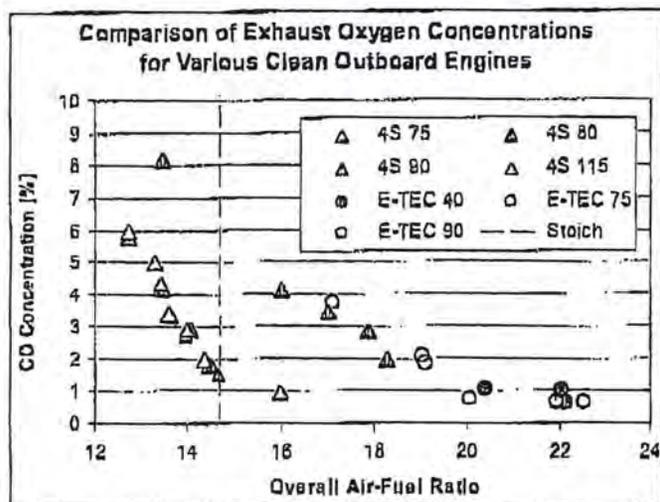


Figure 8: Relation between overall air-fuel ratio and exhaust CO concentration from ICOMIA mode points.

CO REDUCTION MECHANISMS

DISPERSION AND DILUTION

The molecular weight of CO (28.01 g/mol) is very similar to that of air (28.97 g/mol). Hence, at similar pressures and temperatures, buoyancy effects are negligible. In addition, the diffusion coefficient of CO in air is fairly low [30]. As a result, the main factor for CO dispersal is forced convection. Due to the comparable densities, CO concentrations cannot accumulate higher than those of the source. This fact leads to the conclusion that the most effective way to prevent overexposures is to reduce CO concentrations at the source.

WATER SCRUBBING

Most outboard engines provide two paths for exhaust gas into the atmosphere—through the propeller hub and through an above-water idle relief circuit. At idle speed, most or all of the exhaust gas is vented through the idle relief circuit, whereas at higher engine speeds, the majority is vented through the propeller hub. Depending on the speed of the boat, the exhaust gas will bubble up to the water surface at varying distances behind the boat.

Mace et al. investigated how mixing the exhaust gas with water affected gaseous emissions. Both a four-stroke stern-drive engine and a two-stroke outboard engine were tested. The exhaust gas was mixed with tap water and salinized tap water. The data did not show any conclusive evidence that mixing the exhaust gas with water reduced airborne CO emissions [32].

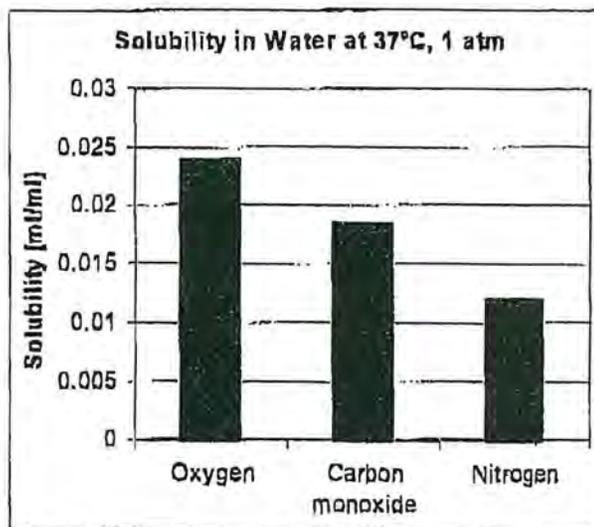


Figure 9: Solubility of Various Gases in Water

Figure 9 shows that the solubility of CO in water is comparable to that of air; hence, absorption of CO into the surrounding water is expected to be quite small.

OXIDATION

Catalysts

The first emissions control systems for automotive engines used a rich calibration for low NO_x and oxidation catalysts with secondary air injection for reduction of CO and HC. Oxidation catalysts have been used successfully on a variety of engines, but they are unproven in production marine outboard engines. The addition of a catalyst with air pump would significantly increase size, weight, and complexity of the engine. Burrahm et al. achieved significant CO reductions on a 4-stroke generator engine by applying oxidation catalysts, secondary air injection, exhaust gas recirculation, and ignition timing changes [16].

Three-way catalysts are capable of reducing HC, NO_x , and CO simultaneously, but require precise control of the air-fuel ratio near stoichiometry, which can be achieved only with closed-loop feedback controls. Challenges for the development and application of catalysts for outboard engines include:

- protection from water and thermal shock
- effects of salt water
- space constraints
- thermal management
- durability and degradation

White et al. equipped a stern-drive four-stroke engine with a closed loop cooling system, external exhaust gas

recirculation, closed loop feedback control, and a three-way catalyst. Initially, they were able to reduce CO emissions by approximately 36%, but more recently have achieved 50% CO reductions and more than 80% reductions for modes 2 - 4 [21].

Post-Oxidation

Significant post-oxidation effects can occur in the exhaust of DI two-stroke engines. The occurrence and efficiency of this effect is dependent on engine operating parameters, such as injection angle and ignition timing. CO exhaust reductions of over 50% have been observed. Figure 10 shows the effect of injection angle on CO, both with and without post-oxidation at WOT for an E-TEC™ direct-injected, two-cylinder, outboard engine. The injected quantity was adjusted during the test to maintain a constant CO concentration without post-oxidation. The data illustrate that reducing the injection angle in conjunction with post-oxidation significantly reduces exhaust CO concentrations.

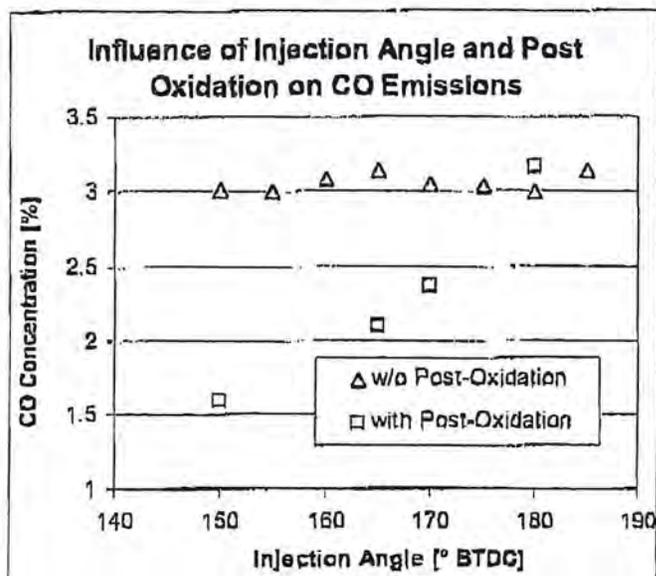


Figure 10: Effect of injection angle on CO reduction with post oxidation.

Figure 11 shows the effect of injected fuel quantity on CO emissions at late injection angle. Although the actual fuel ratio was not determined, the data in the graph are shown relative to the air-fuel ratio for the lowest injected quantity.

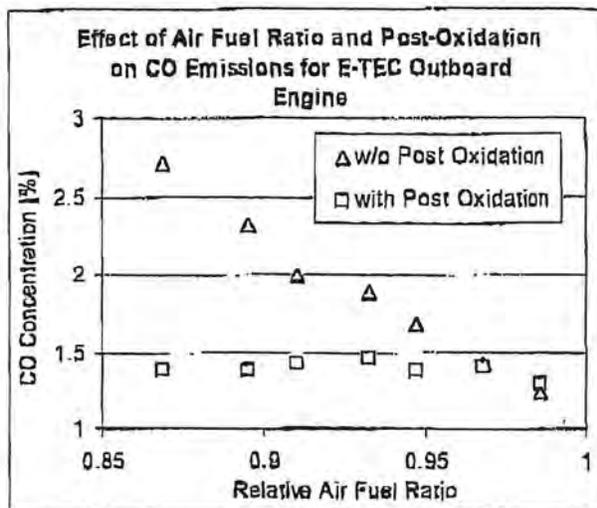


Figure 11: Effect of air-fuel ratio on CO reduction with post oxidation.

Similar to Figure 7, Figure 11 shows that CO concentrations decrease considerably with an increasing air-fuel ratio. However, if post-oxidation effects are included, CO concentrations remain constant at a much lower level, suggesting that the amount of post-oxidation increases with decreasing air-fuel ratio. Figure 12 supports this theory, showing the exhaust gas temperature (EGT) for the same air-fuel ratio sweep. The EGT receiving post-oxidation increases significantly as the air-fuel ratio decreases, compared with a relatively constant EGT without post-oxidation. Figure 13 shows that the HC emissions before post-oxidation are not affected much by the air-fuel ratio, while they are reduced significantly as the post-oxidation effect increases at lower air-fuel ratios.

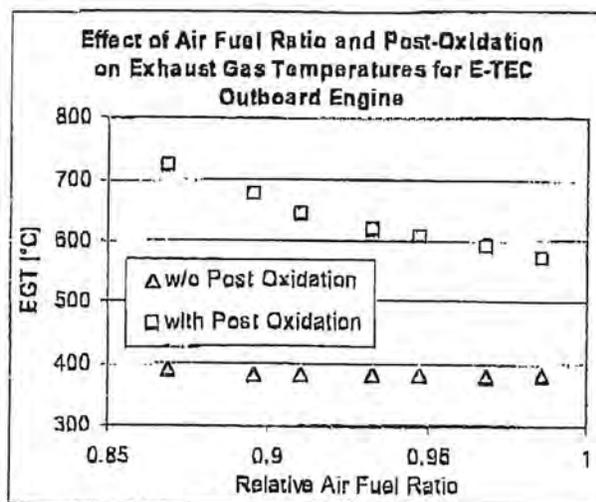


Figure 12: Effect of air fuel ratio on exhaust gas temperatures with and without post-oxidation.

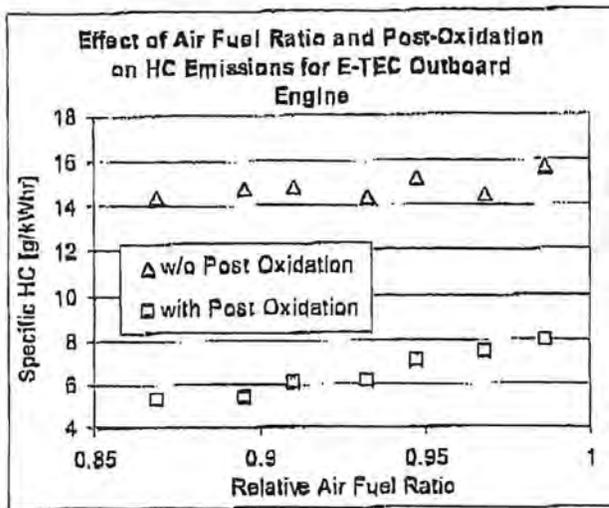


Figure 13: Effect of air fuel ratio on hydrocarbon emissions with and without post-oxidation.

The strong dependence of post-oxidation on injection angle and air-fuel ratio was investigated in more detail. S. R. turns suggests that OH radicals are essential for the oxidation of CO. OH radicals have been used successfully for the experimental detection of the flame front because of their short lifetime and direct association. It is believed that OH does not play a major role in post-oxidation, which takes place at significantly lower temperatures and pressures than in-cylinder combustion. Another mechanism for the oxidation of CO is shown in Figure 14 [31]. The reaction rate constants were calculated as a function of temperature, and the results are shown in the same figure. Please note that the y-axis is logarithmic.

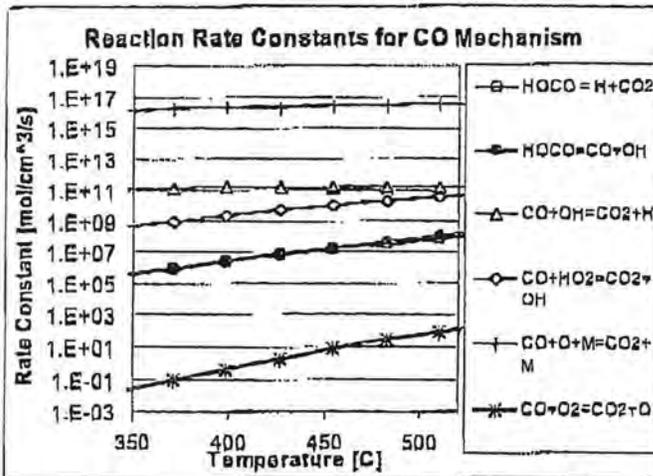


Figure 14: Reaction rates for carbon monoxide mechanism

Figure 14 clearly shows that the reaction step $CO + O_2 = CO_2 + O$ is by far the slowest. It is, thus, the rate-limiting step for the oxidation of CO. Figure 15 shows that this reaction is very sensitive to the exhaust gas

temperatures measured in the engine data. The onset of post-oxidation is also sensitive to initial exhaust gas temperatures. The increase of post-oxidation activity with increasing CO concentrations, as shown in Figure 11, suggests that this reaction step is one of the determining factors for the extent of the post-oxidation effect. The reaction produces an oxygen radical and causes subsequent chain-branching, which may aid in the oxidation of HC, as well.

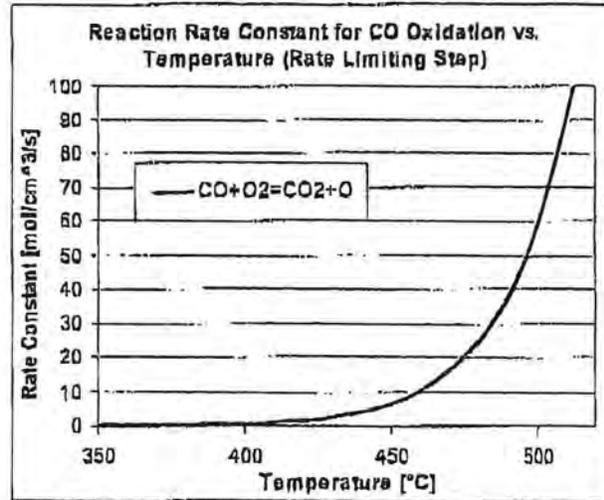


Figure 15: Effect of temperature on rate limiting step for CO oxidation.

Russ et al. investigated the influence of increasing exhaust gas temperature on a single-cylinder, four-stroke research engine and observed increased after-burning effects. The existence of a premixed flame was observed at the Exhaust Valve Opening, which suggested very retarded spark timings. These were attributed to late and incomplete combustion that may have continued into the exhaust stroke [24].

In light of the Russ results, we performed combustion analysis on our data. No significant difference for the ending of combustion timing was observed between the different air-fuel ratios. Hence, it was considered unlikely that the observed increase in post-oxidation and decrease in air-fuel ratio were caused by increasingly late combustion that continued into the exhaust pipe. This finding was consistent with the negligible effect of air-fuel ratio on exhaust gas temperature that had no post-oxidation.

DILUTION

Dilution by itself (i.e., without additional oxidation) does not aid in reducing the amount of CO produced. However, the CO concentration can be lowered substantially through dilution. Significant dilution effects can be achieved during stratified operation of direct-injected engines because of the high levels of excess air surrounding the combustion region. Homogeneously operated four-stroke engines often have low exhaust

oxygen levels, especially under a stoichiometric-rich operation. Figure 16 shows exhaust oxygen concentrations for the ICOMIA cycle for different technologies and power outputs.

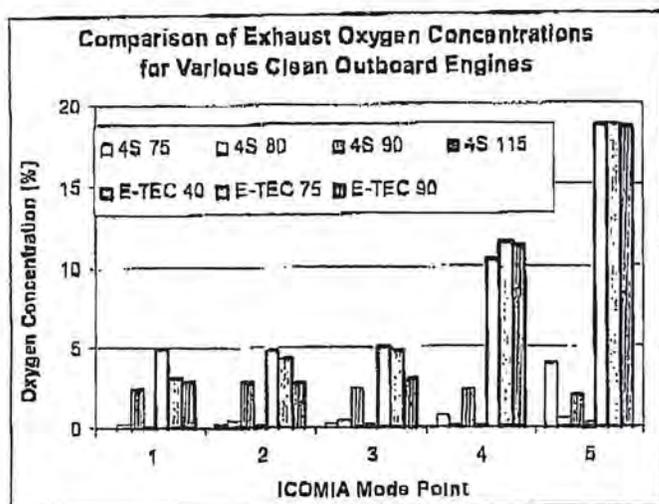


Figure 16: Exhaust oxygen comparison for clean engine technologies.

As Figure 17 shows, a direct correlation exists between residual oxygen concentration and CO levels. Very high oxygen levels, as achieved with the stratified operation, result in very low CO concentrations.

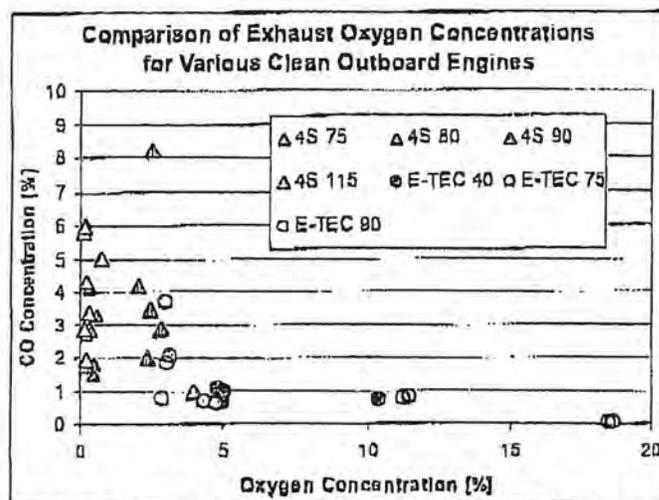


Figure 17: ICOMIA CO concentration vs. oxygen concentration.

SUMMARY

Carbon monoxide exposure is an identified potential hazard for boaters. The EPA and CARB currently regulate HC+NO_x only—not carbon monoxide emissions. The European Union legislates CO emissions in various stages, but the local authority of the Bodensee imposes the most stringent limits. A comparison of specific CO emissions from current model year certification data

shows that the majority of direct-injected, two-stroke engines meet the EC-1 standard, whereas only a fraction of four-stroke engines can meet the CO limits.

CO exposure measurements on recreational boats indicate that the risk of exposure is highest in the vicinity of the engine, and it increases with decreasing engine speed. Emissions data from current model year outboard engines, having an ultra-low emissions technology, E-TEC™ direct-injected two-stroke engine, and a four-stroke engine, show that the CO emissions from the DI two-stroke engine are drastically lower. CO mass emission reduction of up to 96% and reduced concentrations of up to 99% have been achieved.

A lack of oxygen results in CO production during the combustion process. Analysis of the effect of air-fuel ratio on emissions shows a significant tradeoff between NO_x and CO because a rich operation that produces low NO_x does so at the cost of high CO. Since CO emissions from marine engines have not been regulated by the EPA, the hazardous gas is increased by the process to attain low HC+NO_x. Direct-Injected two-stroke engines are not subject to this tradeoff due to the inherently lower NO_x emissions as a result of lower compression ratios and internal EGR.

Several mechanisms for CO reduction have been discussed in this paper. The main factor in CO dispersion and dilution is forced convection, which indicates that a reduced source concentration is an excellent way to minimize exposure risk. The solubility of CO in water is comparable to that of air and, thus, water scrubbing does not result in a reduction of airborne CO emissions. Catalysts have been used successfully to reduce CO emissions, but they require either secondary air injection for oxidation catalysts or closed-loop air-fuel ratio control for three-way catalysts, both of which have not yet been demonstrated on marine outboard engines.

Post-oxidation of the exhaust gas was shown to be a powerful mechanism for reducing CO emissions of DI two-stroke engines. With proper calibration, reductions of up to 50% were achieved. Post-oxidation was investigated in detail and shown to improve emissions by decreasing injection angle, air-fuel ratio, and minimum exhaust gas temperature required to sustain the reaction. Significant reductions in specific HC emissions have been observed simultaneously. It is believed that the rate limiting reaction step $CO + O_2 = CO_2 + O$ is essential for this process. The inherently high concentrations of residual oxygen, in the engine exhaust, from DI two-stroke engines contribute to the low CO levels from the internal dilution and post-oxidation effects. Stratified operation at air-fuel ratios of up to 165:1 results in drastically lower CO emissions compared to four-stroke engines.

CONCLUSION

Direct-injected two-stroke engines have demonstrated their ability to meet stringent emission standards. Additionally, they offer much lower carbon monoxide emissions than four-stroke engines without additional controls or after-treatment systems. Government agencies, marine industry leaders, and others interested in public health and safety should continue their efforts concerning this issue and take the necessary actions to address it. Development of advanced engineering control technologies to limit CO emissions from marine engines, such as that described in this paper, is a major step forward.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CO: Carbon Monoxide

HC: Hydrocarbons

NO_x: Oxides of Nitrogen

DI: Direct Injection

2S: Two-Stroke

4S: Four-Stroke

CARB: California Air Resources Board

EPA: Environmental Protection Agency

ICOMIA: International Council of Marine Industry Associations

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