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Novel Approaches to Control Emissions from Marine Diesel and Gas-Turbine Engines

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Environmental regulations on emission from ocean-going and stationary gas turbines and diesel engines used for marine (Navy) propulsion and auxiliary power have revived interest in studies on fundamental mechanisms of pollutant formation and innovative approaches on mitigating them. The U.S. Office of Naval Research sponsored several related research projects. The projects include reduced chemistry formulations, which result in substantial reduction in computing times, lean partial premixing that can simultaneously reduce NOx and UHC, steam-assisted or oxygen enriched-air atomization, electrostatic atomization, selective noncatalytic reduction, nonthermal plasma remediation with easy on and off capability with about 70% NOx reduction, and porous inserts in which 30 to 60% reductions in NOx have been demonstrated. Some of the techniques produce steady flames and improve pattern factor, thus providing stable combustor operation. The fundamental understanding obtained is applicable to emission control from combustion systems in general. The accomplishments made by the various investigators who participated in this research effort constitute the subject matter of this paper.

I. Introduction

AIR quality is one of the leading issues of environmental concern. Restrictions on the emission of atmospheric pollutants are increasing in many geographic areas and can, in the future, interfere with the deployment of naval propulsion and power systems. Though the major contributors to air pollution are fossil-fueled central power stations and large ground transportation vehicles, emissions from marine vessels can be of significance in specific localities. In the United States, powerplants are responsible for the following emissions: 72% of all sulfur dioxide, 33% of all nitrogen oxide, 33% of all particulates, 36% of all carbon dioxide, and 23% of mercury. The pollutants of concern from marine engines are CO, unburned hydrocarbons, soot, NOx, and SOx. In spite of the fact that emissions from naval vessels are significantly smaller compared to other ocean-going vessels, efforts are undertaken to reduce these emissions and to comply with the regulations that could be implemented in the future. Relevant regulatory authorities are the International Maritime Organization (IMO), the Environmental Protection Agency (EPA), and the California Air Resource Board (CARB). Navy policy requires compliance with federal, state, and local air pollution regulations. The naval power sources affected by these regulations are diesel engines, gasoline engines and gas turbines (used for both propulsion and stationary applications), and conventional boilers.

II. Environmental Regulations and Efforts for Compliance

IMO proposed environmental regulations consists of the new MARPOL Annex 6 for international regulation of NOx and SOx. A 30% reduction of NOx in new diesels through improved combustion, and NOx reduction methodologies starting from the year 2000 were proposed. Control of SOx has been envisioned primarily through the reduction of the sulfur content in the fuel—a global cap of 3–4% fuel sulfur and limitation to 1.5% on a regional basis. The EPA-proposed plans also call for 30% reduction in NOx. The CARB-proposed emission requirements are the most stringent of all. The NOx limits proposed are 600 ppm and 42 ppm for propulsion diesels and gas turbines in use, respectively, and 750 ppm and 42 ppm for non-ocean-going auxiliary diesels and gas turbines, respectively, in use. Though the proposed NOx limit for new propulsion and auxiliary gas turbine are the same at 42 ppm, the new diesels have to comply with further reduced limits—130 ppm at more than 25% power and 450 ppm at less than 25% power for propulsion diesels and 600 ppm for auxiliaries. Maximum allowable fuel sulfur is set at 0.05% by weight. Because CARB requirements apply up to 100 miles off the California coastal waters, this is a concern for naval vessels as most of the training operations occur within this range.

A. Navy Marine Engine Emissions

The Navy assets affected by these stringent regulations include combatants, auxiliaries, aircraft carriers, amphibious ships, mine sweepers, utility boats, harbor tugs, security boats, landing crafts, etc. The major power sources presently under consideration are diesel and gas-turbine engines, as well as intercooled recuperative engines. The amount of pollution produced by hydrocarbon-fueled airbreathing engines depends upon the fuel properties as well as the thermodynamic cycle and combustion characteristics of the engine, with diesel engines providing significantly more emissions than gas-turbine engines. Presently most Navies have standardized on NATO-76 as a common fuel. Naval marine fuels have currently 1% (proposed $^1/_2$%) sulfur content and a relatively high flash point for reasons of safety.

In Fig. 1, percent sulfur in fuels (by weight) is compared for various fuel types along with the CARB limit. As can be seen, order of magnitude of sulfur reduction is required to meet CARB limit (0.05% sulfur). The Navy marine engine specific emissions as a function of percent load is shown in Fig. 2. Propulsion diesel engine emission is about twice at half-load compared to full load operation. Though the NOx emissions from Navy marine engines do not appear modest, the percentage contribution by these is only about 1.6% of the total emission from all vessels in the CARB area waters (Fig. 3).[1] For a general idea of emission from Naval vessels, NOx from a Destroyer at specified operating conditions is shown in Fig. 4. The CO and SOx contribution from Navy vessels is less than 1% of the other ocean-going vehicles.

B. Exhaust Emission Control

Control and reduction of engine exhaust emissions is a global priority in the recent years and will continue to be so in the future. In the United States, investments have been made by NASA,

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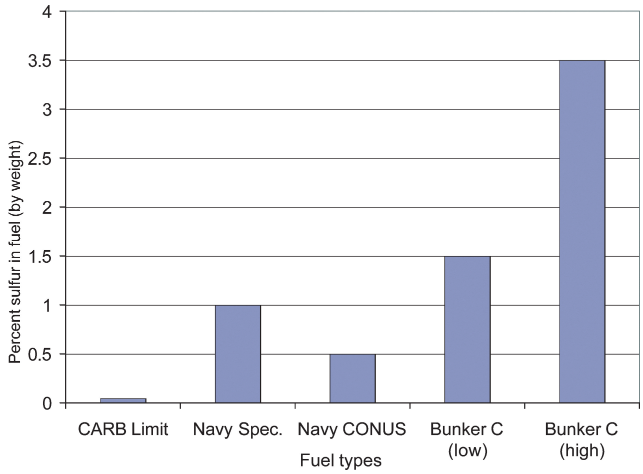

Fig. 1 Percent sulfur in fuels by weight.[1]

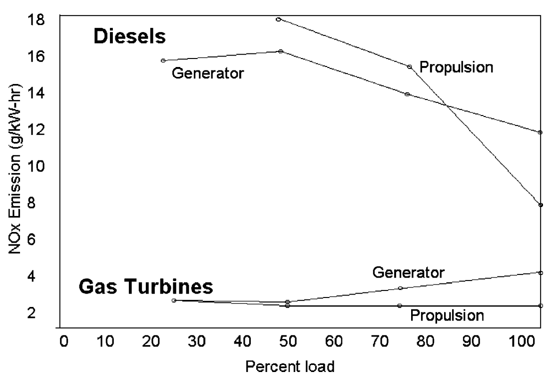

Fig. 2 Navy marine engine specific emissions as a function of percent load.[1]

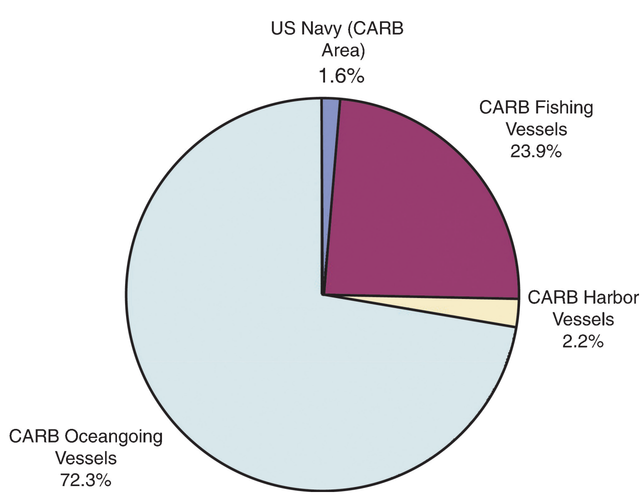

Fig. 3 California marine vessel NOx.

U.S. Department of Energy, Defense Advanced Research Projects Agency, Electric Power Research Institute, Gas Research Institute, and engine manufacturers, to explore options to reduce pollution from airbreathing engines. Most of these efforts focused on commercial engines using liquid fuels. Though the Navy marine gas turbines are derived from the aircraft gas turbines, differing fuel properties and operating conditions as well as operation at partial load most of the time (see Fig. 5) and off-design performance require special consideration from the emissions point of view.

Most of the conventional methods used for emission control introduce a power penalty and corresponding increased fuel consumption. For better performance and fuel economy, emission control should be achieved during precombustion, combustion, and postcombustion periods. The choice depends upon whether retrofit or new design is sought. Precombustion and postcombustion techniques will be suitable for retrofit; the amount of space required for the extra equipment being the primary concern. Emission control during combustion involving major combustor changes is not acceptable. The conventional methods used for diesel emission reduction are fuel-injection timing retards, electronic fuel injection, water injection/emulsification/fumigation, exhaust gas recirculation, combustor design modifications, and selective catalytic reduction. For gas turbines, low NOx combustors, water injection, and selective catalytic reduction have been attempted. Water injection is a controversial issue for gas turbines because of the effect of water particles on turbine blades, the purity of the water, and the amount of water needed onboard (even though seawater is available). Extensive studies have been carried out on these methodologies, but the added cost of the components and the increase in fuel consumption necessitates a systematic scientific approach to understand fully the mechanisms of pollution formation, transport, and destruction in order to formulate the best strategy (which might very well be a hybrid approach).

C. Current Navy Research Emphasis

There are over 1000 gas turbines (various manufacturers) and over 3500 diesel engines (various manufacturers) in the U.S. Navy fleet for main propulsion, generator, and emergency generator duties. No Navy ship with gas-turbine or diesel engines currently operating will comply with the proposed exhaust emissions limits. Hence, they require implementation of engine exhaust emission control. The goal has been to attack the issues from the fundamental perspective, and to understand the mechanisms of soot and NOx formation and propagation, and to explore novel control methodologies for their mitigation, particularly for Navy marine engines. To accomplish this, the U.S. Office of Naval Research (ONR) sponsored several research projects with performers from academia, government laboratories, and industry. The projects addressed to a larger extent the control of NOx emissions, followed by SOx and soot-related issues.

III. Emission Control Studies

Though the specific emission control methodologies in diesel engines and gas turbines might be different, the fundamental mechanisms apply to both. Because of the continuous combustion mode in gas-turbine engines and the intermittent transient combustion conditions in diesel engines, the actuation and control schemes can be very different. Novel emission control techniques such as electrostatic atomization of fuel, steam-assisted fuel atomization, nonthermal plasma methods, fuel flow retardation, etc. were investigated in addition to fundamental chemistry studies. Recent results and accomplishments from some of the research efforts follow.

A. Fundamental Chemistry Studies

Before one can control the products of combustion, it is necessary to gain an understanding of the reaction chemistry, energy release rates, and the kinetics involved in the emission species formation. Reduced chemistry is a means of explaining the chemical process of combustion without the shortfalls of the full chemistry approach, namely, the large numbers of differential equations that make computation very difficult. Forman Williams ' studies involve the reduction of the number of chemical species and the number of reactions considered. The objective is to create a chemical description simple enough to calculate the complex flow problems, but still retain enough information to adequately describe each step of the process. Many advances have been made in this field in the past few years. Some of the pertinent areas include general principles of steady states and partial equilibria, hydrogenoxygen flames, hydrocarbon flames, propellant deflagration, NOx kinetics for diffusion flames, and hydrocarbon-air ignition.[2]

Starting with a full chemical kinetic description, various steady-state and partial-equilibrium approximations are introduced to reduce the chemistry needed to describe structures of laminar heptane-air diffusion flames and NOx production processes therein

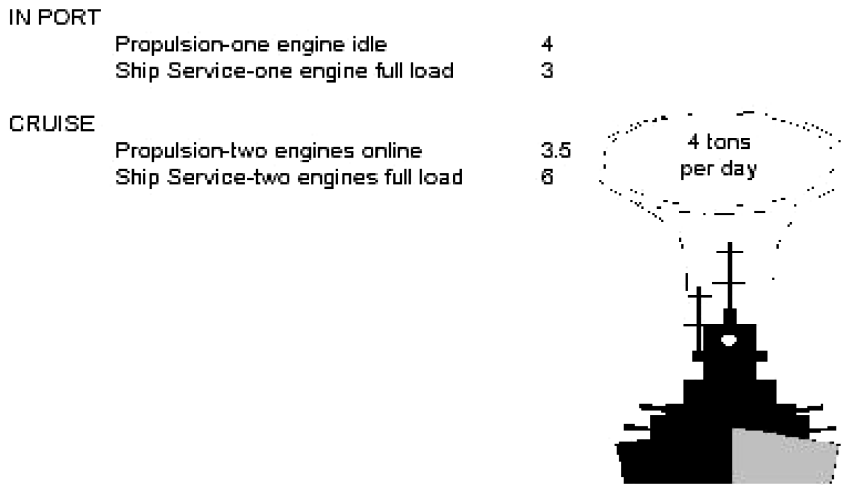

Fig. 4 Typical destroyer NOx emission levels.

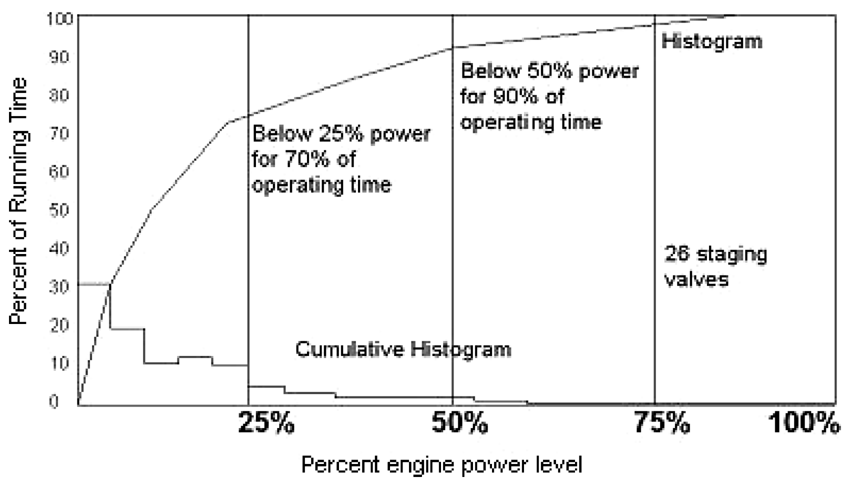

Fig. 5 Average engine power level histogram.[1]

to a total of eight overall steps, with rate parameters deduced systematically from those of the elementary reaction steps. Predictions of flame structures obtained from the reduced chemistry and from experiment show good agreement. In addition, predictions of NOx emissions by the same reduced chemistry of the formulation and comparison of prediction with full and reduced mechanisms also show good agreement. Details can be found in Refs. 3 and 4.

B. Lean Partial Premixing

Partially premixed flames, as a paradigm for lean direct injection of fuel in Naval Marine engines for reducing NOx and soot emission, were investigated by Gore.[5] Lean premixed systems operate close to the lean flammability limits and have fairly uniform equivalence ratios across the cross section of the combustor. As a consequence, peak temperatures are reduced resulting in decreased NOx emission. Mixing air in less than stoichiometric levels into the fuel stream prior to the reaction zone, where additional air is available for complete combustion, forms partially premixed flames. Partially premixed flames are more stable than ultralean premixed flames and are shorter than conventional nonpremixed flames. Additionally, partially premixed flames provide a uniform flame temperature profile (pattern factor) with improved stability and performance, as well as reduced NOx. Lean partial premixing is being used by means of an adjustment in injection timing and the use of multiple injections. The strategy being implemented in gas turbines is called lean direct injection, in which air is mixed with the fuel before injection. With increased mixing, there is an increase in NOx, after the initial dip. Partial premixing seeks to optimize the mixing level to minimize the amount of NOx. Figure 6 shows emission indices as a function of decreasing levels of partial premixing. At the optimum level of partial premixing, the levels of NOx, CO and HC emissions are simultaneously reduced.[6] Flame photographs have shown that soot emissions are completely eliminated.

Computational approaches led to the optimum level of partial premixing for minimum NOx emissions and to the observation that partial premixing leads to reduction of soot. Flame calculations were completed with the OPDIF code with radial velocity gradients at the exits of both the fuel side and the air side nozzles to obtain low-strain-rate laminar flames.[6]

Experimental and computational studies of moderate stretch rate, opposed flow partially premixed flames were made to understand the observed NO behavior. Measurements of major gas species were used first to gain confidence in the mechanism. Then computations were employed to delineate the NO chemistry. Predictions of emission index for NO (EINO) rates and integrated rates of N_2 fixing reactions for a range of partial premixing were used to identify reasons for the observed behavior. Results showed that minimum NO emissions at the optimum level of partial premixing results from a decrease in a prompt initiation reaction, as a consequence of a decrease in the CH radical concentration.[7]

C. Steam-Assisted Atomization

Ashwani Gupta's group identified the role of atomization gas properties in producing finer atomization of liquid fuels to control the flame plume characteristics and emission. Initial studies used

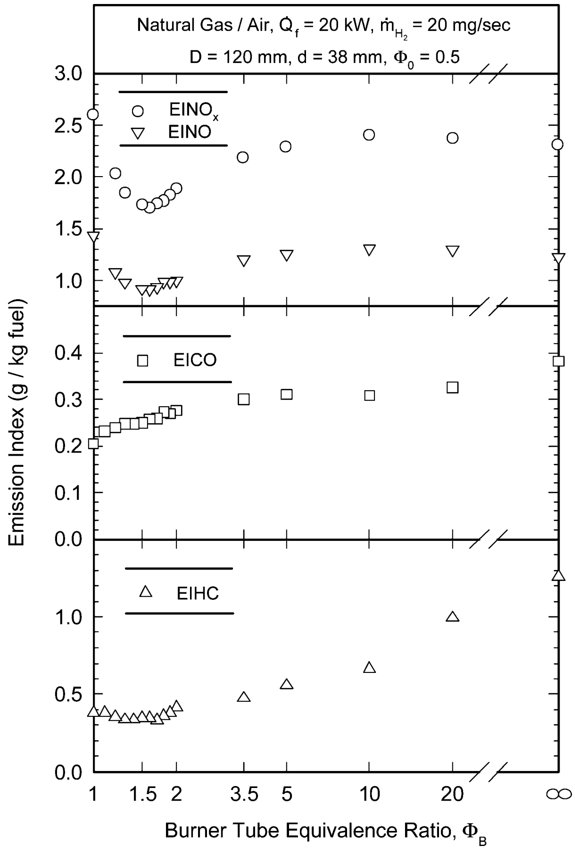

Fig. 6 Emission indices as a function of decreasing levels of partial premixing.[5]

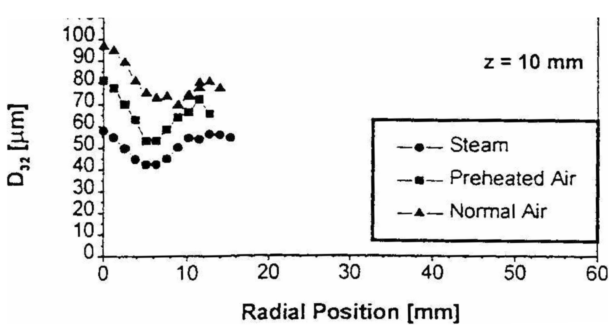

Fig. 7 Variation of droplet Sauter mean diameter (D_{32}) with radial and axial positions for different atomization gases.[8]

air, oxygen-enriched air, and propane as the atomization agent.[8] Droplet size, velocity, number density, and volume flux in sprays have a critical effect on the coupled heat, mass, and momentum transport processes, which in turn affect the flame stability, temperature, and pollution characteristics. Experiments were carried out at the National Institute of Standards and Technology (NIST) Combustion Facility using normal air, preheated air, and steam as atomization gas. A two-component phase Doppler interferometer was used to determine the fuel droplet size, number density and velocity in the spray flames. Global features of the spray and spray flame were obtained using direct photography. Variation of droplet Sauter mean diameter with various atomization gases is shown in Fig. 7. Droplet size was smallest with steam as the atomization gas near the nozzle exit at all radial positions. Mean droplet size with steam at axial position $z = 10$ mm on the central axis of the spray was found to be 58 μ as compared to 81 μ with preheated air and 91 μ with normal unheated air.[9] The investigation was extended with oxygen-enriched air as the atomization gas. The results reveal that O_2 enrichment of the atomization air increases the local flame temperature at upstream regions of the spray that rapidly depletes the smaller size droplets in the spray size to increase the mean droplet size.[9] The overall equivalence ratio to the combustor was essentially unchanged because of very small quantity of the atomization air used. Near the nozzle exit at $z = 10$ mm, the droplet mean size and velocity were about the same for all levels of O_2 concentration in the air. However, further downstream, the droplet size and velocity were significantly smaller with normal air than for the O_2-enriched case. The preceding suggests that oxygen enrichment improves combustion through rapid ignition of the fuel droplets with the local presence of oxygen enriched air, and hence this makes it possible to use lower grade, cheaper fuels to achieve the same performance as with currently available higher grade fuels. Steady combustion at reduced low overall temperatures could lead to reduced NOx emissions.

D. Electrostatic Atomization

Electrostatic charging of the drops in the cluster of a spray has been considered as a way to mitigate soot formation. A model for dispersion of an electrostatically charged polydisperse cluster of drops has been formulated in that context.

In her studies, Josette Bellan identified high-energy fuels (as candidates), which are more prone to soot formation than other conventional hydrocarbon fuels. The crucial parameter for dense clusters of drops is the latent heat, which, when low, promotes evaporation. When evaporation is faster than drop dispersion, fuel-rich vapor pockets form inside the cluster of drops and are the precursors to soot. Her study also showed that when drops are charged, the additional dispersion caused by the electrostatic force increases the cluster volume and enhances heat transfer with the cluster surroundings, as well as decreases the drop number density and promotes evaporation. The result is a reduction of the mass fraction of the evaporated compound inside the cluster. As proposed by previous investigators, for initial electric charges proportional to the drop size, the smaller drops are preferentially dispersed. Because these smaller drops evaporate faster, this preferential dispersion promotes mixing and thus provides an added benefit from electrostatic charging.[10]

E. Selective Noncatalytic Reduction

To meet stringent NOx emission standards, postcombustion methods for NOx removal from combustion products have also been developed. These techniques utilize injection of a nitrogen-containing additive into the combustion products. The NO removal process can take place entirely in the gas phase (selective noncatalytic reduction, SNCR), or it can take place partly or entirely on the surface of a catalyst (selective catalytic reduction, SCR). In all cases, NO removal occurs by reaction of NO with a nitrogen-containing radical, such as NH_2 or NCO, which is generated from the additive. Tom Bowman and Ron Hanson investigated the possibility of using SNCR processes for in situ reduction of NOx and CO emissions from marine gas turbines and diesel engines. The SNCR NOx reaction mechanisms proposed by Bowman are shown in Fig. 8.

Two nitrogen-containing reactants NH_3 and HNCO were investigated to establish the role of reductant molecular structure on NOx

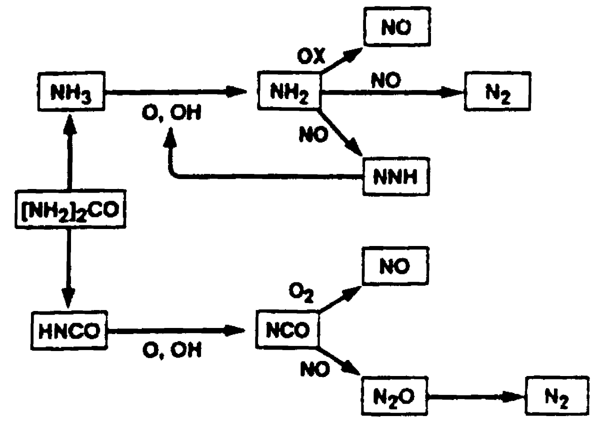

Fig. 8 Chemical reaction pathway of emissions.[11]

removal efficiency. An initial experiment using NH_3 as reductant was carried out at 1 atm to verify the experimental procedure. Results from the experiment were compared with model predictions. As can be seen from Fig. 9, reasonably good agreement is obtained.

The simulations were extended to higher pressure (up to 20 atm). An improvement in NOx removal is observed with increasing pressure. This suggests the usefulness of this method at practical gas-turbine operating conditions. Figure 10 shows the NOx removal efficiency as a function of temperature and pressure,[12] suggesting a modest widening of the NO removal window found at higher temperatures.

The design and fabrication of a prototype NOx microsensor, based on WO_3 films, has been completed.[12] This patented sensor can be used for multispecies measurement in emission control systems.

F. Nonthermal Plasma Remediation of Emission

The probability of using electrical energy in the form of plasmas or short-duration high-intensity pulses is receiving attention from the diesel engine research and development community. The advantages of such a system are that no modification of the combustion chamber is required and the device can be added on as an "electric muffler" in the exhaust region. This is of particular advantage for ocean-going diesels because the electric muffler can be turned on and off as desired—utilizing it during training exercises and turning them off during combat situations.[13]

The nonthermal plasma methodology is based on the utilization of higher-energy electrons, where the electron temperature is much greater than the gas and ion temperatures. The electron energy distribution is highly non-Maxwellian. The radicals are heated up and dissociate, whereas the bulk exhaust gas is at low temperatures. In Fig. 11, the large overlap of electron energy in the early stages of the discharge indicates increased reaction rates leading to dissociation.[14] Figure 12 shows a schematic of the nonthermal plasma device designed and tested by Liu et al.[15] The short-repeated pulses applied to the exhaust stream use typically two orders of magnitude less energy than those for plasmas used for burning chemicals. Plasma remediation of the oxides of nitrogen has been demonstrated using a Volkswagen automobile diesel engine. The technique was utilized for engines, in situ treatment of slipstream from a 750-kW diesel generator at Port Hueneme Naval Facility using a corona reactor of 40 cm length and 10 cm diam (Fig. 13). Results from the studies suggest that it would be possible to obtain efficient plasma treatment system using approximately 2% of the engine's power.[16]

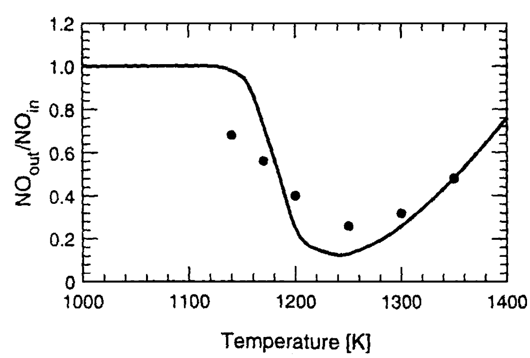

Fig. 9 Comparison of measured and calculated NO removal from combustion products for injected NH_3 (Ref. 12).

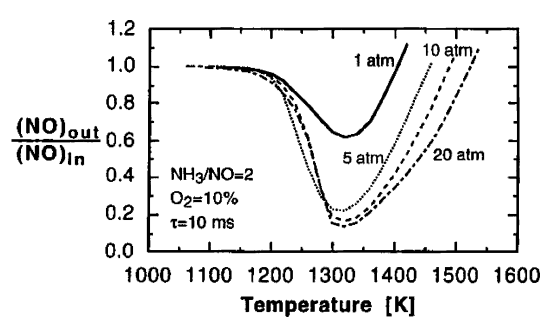

Fig. 10 Effectiveness of SNCR for NOx and CO removal from high-pressure combustion products.[12]

G. Porous Insert for Emission Control

Utilization of the superior radiation, thermal and physical properties of porous media has, in recent years, gained acceptance in reducing emissions and improving thermal efficiency. To explore this concept, and to optimize the parameters involved, Shayam Singh pursued an experimental and theoretical investigation. Experiments were conducted in a continuous flow combustion test facility consisting of an inlet, combustion chamber, and exhaust. One or more porous inserts were installed at desired axial locations in the optically accessible combustion chamber.[17] The effects of location, thickness, and pore size of the porous inserts, and the operating conditions such as firing rate and fuel air ratio were studied. As an example, the effect of porous layer thickness on NOx, CO, and UHC concentrations is shown in Fig. 14 (Ref. 18). It was found that, with the porous layers installed, flame radiation increased, lowering the peak flame temperatures and extending the reaction zone. The radial conduction of heat and radiation in the solid matrix aids in improving the pattern factor and thus improves stability. Because of the elimination of hot spots that serve as NOx generators, NOx generation was reduced by 30–60%. Porous layers did not yield any reduction in CO emission because of lower flame temperatures. Though additions of a second porous layer further reduced NOx emissions, improved mixing was necessary to promote CO and UHC burnout. Various factors contributed to variations in NOx reduction. These include the geometry and characteristics of the porous inserts and combustor operating conditions. The parametric dependence of these can be found in Ref. 18. For the test conditions investigated, the pressure drop across the porous layer did not cause any significant decrease in the thermal efficiency.

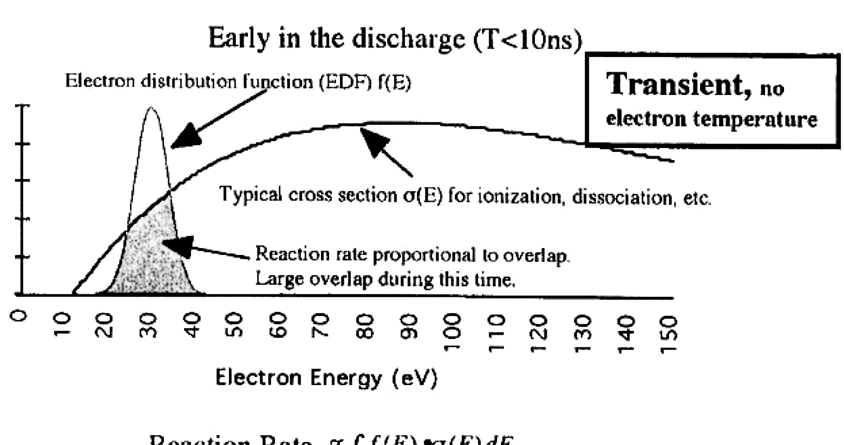

Fig. 11 Reaction rates leading to dissociation.[14]

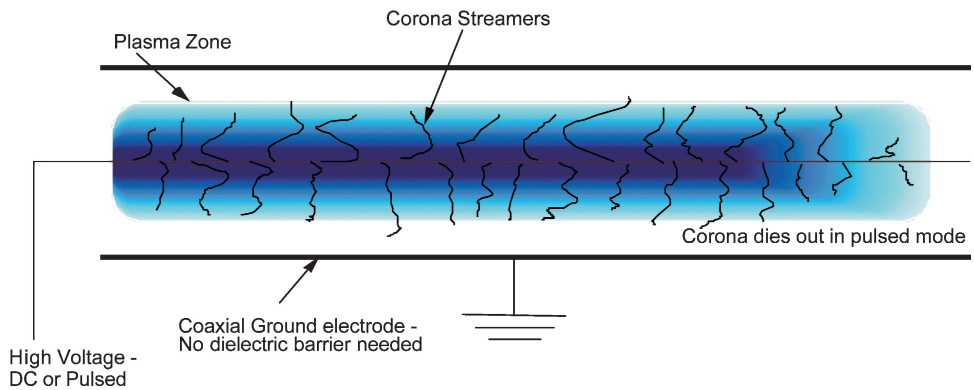

Fig. 12 Diagram of the corona reactor.[15]

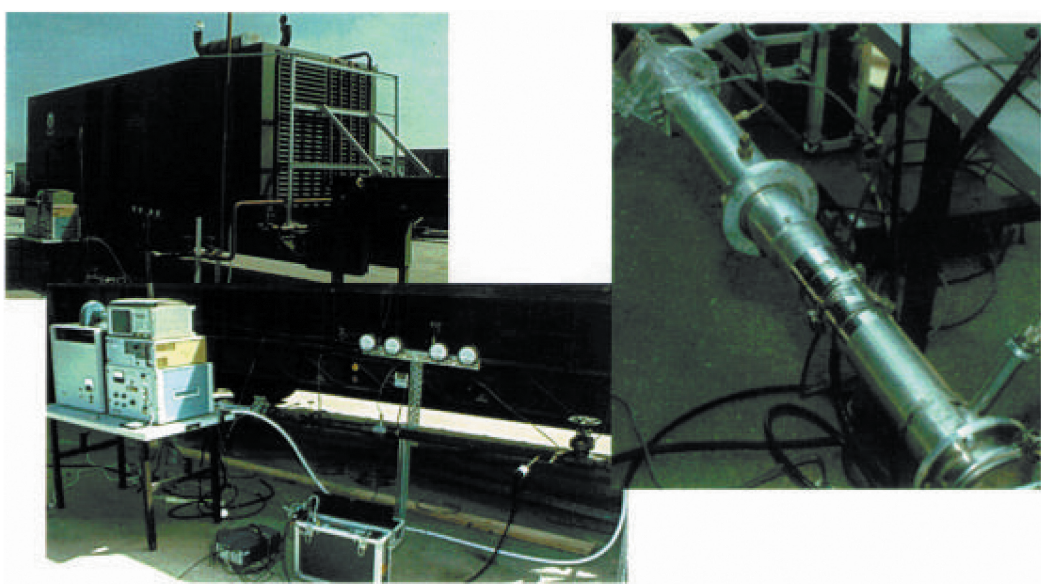

Fig. 13 Port Hueneme testing facility.[16]

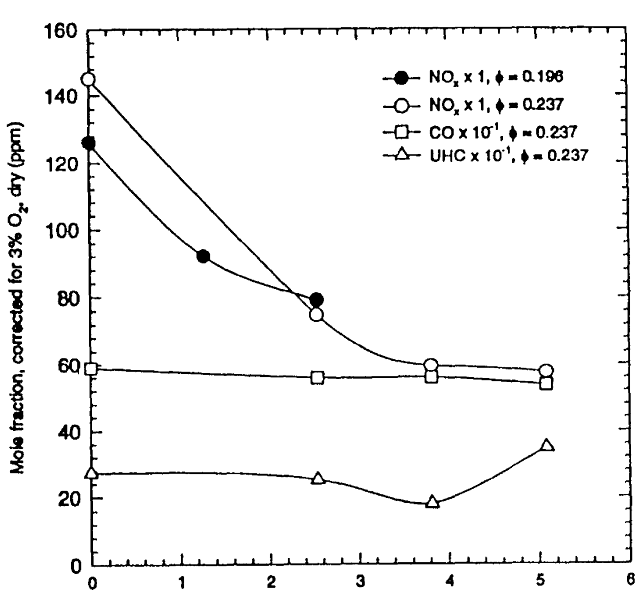

Fig. 14 NOx, CO, and UHC concentrations vs porous layer thickness ***t*** **(SiC foam, L/D = 1.1,** $p = 8$ **ppcm,** $Q_{in} = 13.2$ **kW) (Ref. 18).**

IV. Technology and Development Efforts

The U.S. Navy has sponsored many technology initiatives over the past decades, several of which addressed issues that are related to exhaust emission control. The U.S. EPA recently proposed a voluntary retrofit program for in-use diesel engines. Programs such as these provide ready opportunity to apply the science and technologies developed by the Navy (described earlier in this paper) and the commercial sector. There are several efforts undertaken elsewhere. The Naval Facility Engineering Service Center (NFESC) participated in a cooperative project with Cummins Engine (CE) Company to evaluate and demonstrate the use of a catalyzed soot filter (CSF) on DoD diesel engines. Preliminary laboratory tests at CE to characterize regeneration characteristics, at Oakridge National Laboratory to measure particular matter (PM) size distributions, and at Michigan Technological University to characterize chemically and physically diesel engine emissions upstream and downstream of the CSF have been completed. Results showed an increased number of fine PM downstream of the CSF under some operating conditions, but a 1–2 order-of-magnitude reduction in concentration of hazardous air pollutants (HAPs) were in the PM downstream. A small project was undertaken by NFESC to reduce smoke in a 450-HP Detroit diesel engine. A new injector design was implemented to bring the engine into compliance with environmental regulation. A subscale, cold plasma generator was evaluated with University of Southern California (USC) for use in reduction of NOx from a Naval diesel engine. A 1500-kW diesel engine generator was converted to dual-fuel operation. Online fuel switching was provided, and a 70% reduction in NOx with a 30% reduction in PM was achieved. Additional benefits of this setup were reduced fuel costs and conservation of petroleum (the second fuel used was natural gas). At the Naval Surface Warfare Center Carderock Division (NSWCCD), two research and design projects were undertaken. One was a SCR system, manufactured by Siemens, on a two-stroke DDC 471 diesel engine and four-stroke Cummins 5.9L B series, in which NOx reductions of 80–90% were achieved. The next NSWCCD program was performed in conjunction with the U.S. EPA at Research Triangle Park. EPA developed the emissions control system, while NSWCCD conducted the shipboard evaluation using a yard patrol craft from the Naval Station in Annapolis. NOx reductions of 30% were achieved during the evaluation. Finally, a task is currently underway to develop a fuel additive for marine engines that will reduce NOx emissions by 30% without hindering fuel economy and power density. This would, hopefully, negate the need for SCR type systems.

It has been shown that a computational optimization can be performed for a heavy-duty, direct-injection diesel engine using a KIVA-GA (generic algorithm) computer code. The design methodology found a set of engine parameters that can reduce soot by a factor of three and NOx by a factor of two, while reducing the specific fuel consumption by 15% compared to the baseline configuration. In the gas-turbine arena, sequential fuel injection with respect to the incipient vortex has been successfully applied to large-scale engines and indicates promise as a viable active-combustion-control technique both to improve performance and reduce pressure oscillations.

V. Conclusions

Stringent environmental regulations and their compliance have necessitated focused research in understanding the mechanisms involved in pollutant production and extinction. Fundamental research on fuel-oxidizer reaction chemistry and demonstration of pollutant reduction with innovative techniques in large-scale engine tests have attracted the attention of academia, industry, government laboratories, and various science and technology sponsoring agencies. ONR, through various projects performed by academia and industry, is providing the science base for systematic development of both evolutionary and revolutionary concepts in emission mitigation. Some of the techniques have concomitant advantages of reducing combustion instability and improving performance.

Reduced chemistry formulations have paved the way to substantial reduction in computational time required to study combustion characteristics of fuels, in particular liquid-hydrocarbon fuels. Lean partial premixing, under optimized conditions, has shown to produce simultaneous reduction in NOx and hydrocarbon emissions. Steam-assisted atomization with oxygen enrichment has shown to produce stable flames at reduced temperatures, thus reducing the tendency to NOx formations.

A novel technique using nonthermal plasma is of particular interest to the Navy because the reactor can be kept during exercise operation and near-shore trainings when the emissions is an issue and turned off during combat situations incurring no penalty in power.

Acknowledgments

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