Journal of Mechanical Engineering Research and Developments
ISSN: 1024-1752
CODEN: JERDFO
Vol. 44, No. 8, pp. 269-279
Published Year 2021

Wet technologies as effective primary solutions in reducing emissions for marine diesel engines

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ABSTRACT

Marine diesel engines are one of the main sources of air pollution. Exhaust gases of diesel engines have many different harmful components, especially nitrogen oxides with the general formula NOx. Currently, there are many methods and research directions to limit NOx emissions in diesel engine exhaust, each method has its own strengths and limitations. In order to obtain the efficient energy development with less polluted environment with existing marine diesel engines, continuous efforts have gone into research and development of wet technologies, which have the potential to reduce nitric oxides (NO_x) and particulate matter (PM) emissions simultaneously with improved performance level. The main objective of this review is to shed light on the role of typical water addition technologies such as water-in-fuel emulsion, intake air humidification – humid air motor and direct water injection in reducing NOx and PM emissions in marine engines. We have made a comparison of the effectiveness of different methods used to reduce the emission of nitrogen oxides. Advantages and disadvantages of supplying water into the combustion chambers of diesel engines have been shown together with the comparison of the range of changes in their construction.

KEYWORDS

Wet technologies, marine diesel engines, reducing emissions, water-in-fuel emulsion, intake air humidification, direct water injection

INTRODUCTION

The energy demand is changing and rising significantly with the development of civilization. Combustion engines are utilized regularly for transforming energy. Thus, the harmful emissions are released into the environment via their operation, and it leads to environmental pollution especially air pollution. Scientists have estimated the maritime industry's contribution to global air pollution through studies at many different levels [1]. Pollutants emitted by ships accounting for a few percent of total hazardous waste cause environmental pollution[2][3]. One factor of the continued development of combustion engines, including marine engines, is the continuously strictly limit hazardous exhaust gas [4][5][6]. Designers need to search for novel combinations and enhance continually the present systems of marine propulsion for compliance with maritime legal requirements. Water supply into the combustion cabin of diesel engines is one of the solutions that is an advantageous solution, the solution known and utilized widely, and it has many competitive advantages compared to other constructions [7][8]. In International Convention for the Pollution Prevention from Vessels has been mentioned the volume of sulphur oxides and nitrogen oxides allowed to discharge in the operation process as special attention [9]. Until now, still can not fully solve the issues that are the global of new marine propulsion system designs review and retrofit marine equipment [10].

Sharp reduction of NOx and particulate matter from current values are requirements for emission limit in the future for the purpose of making the marine diesel engine manufacturers working hard to satisfy this requirement [11]. The NOx formation controlling in the cylinder remains of paramount importance, although in order to reduce NOx in exhaust pipes in heavy-duty diesel engines, many post-processing techniques have been developed and improved [12]. The methods like retarded injection timing and EGR giving each of them very engaging results have been utilized for controlling the formation of NOx in diesel engines. However, the penalties in specific fuel utilized and soot emissions will accompany if these techniques are applied. The injection of water to the combustion cabin for decreasing peak combustion temperature, which clearly impacts the generation of NOx, it is considered as a potential method for reducing NOx generation especially for heavy diesel engines and primarily big engine. Marine and stationary diesel engines have applied this method because when applying the method need to request minor modifications to the infrastructure of the engine [13][14]. Due to the lack of theoretical and experimental knowledge, until now, its real potential is still unknown for diesel engines. For this reason, this approach is explored for the reduction of NOx emissions from heavy-duty diesel engines with direct injection. A water-fuel emulsion using or water injection into the intake manifold are two different technologies that are tested for providing water into the combustion chamber [15][16].

For reducing the combustion temperature and NOx emissions, a method is used that is added water into the diesel process. Inject directly water into the cylinder is the most popular method of introducing water, a technique marketed in some marine and stationary diesel motors, and emulsions of water-in-fuel [17][18]. Emulsified fuels, because mixing in the diesel amplification flame increasing, can influence positively to reduce emissions of PM and NOx. Water-in-Fuel Emulsion (WFE), Direct Water Injection (DWI), Intake Air Humidification – Humid Air Motor (HAM, or Scavenging Air Moisturizing, SAM) are principal three possibilities [19][20][21]. In order to lower emissions between Tier I and Tier II levels but appears not to suffice for conformity with tier III emissions limitations, wet technologies have been utilized widely together with strategies for regulating engine parameters and related to the combustion process [22][23]. Moreover, because the observation that water globule hitting the cylinder wall can destroy immediately the lubricating oil membranes, and water injected into the cylinder can also lead to corrosion issues, the addition of water is still an argumental issue [24].

Though, the only reason for these issues is liquid water. In fact, when the water in a vapor status, it not able to affect the lubrication oil membranes, and unless water reaches saturation it condenses, otherwise it won't condense, so, this issue is not high effect at high fire temperatures [25]. Compare to other vehicles transport, the issue of water source is not important for the vessel, however, freshwater systems are necessary because the vessel needs a large of water for NOx reduction. Inject continually water into the scavenging air, humid air engines, inject directly water utilizing combination nozzles, and fuel/water supplies using emulsifiers or high-pressure water injection devices have been considered, discussed, and given [26]. The effectiveness of different methods utilized for reducing nitrogen oxide emissions has been compared by us. Together with a comparison of the extent of change in their composition, the advantages and disadvantages of water supply into the fire cabin of a diesel motor have been illustrated [16][27].

WATER-IN-FUEL EMULSION

A system including two insoluble liquids, one in two liquids is scattered finely in the other, it is called emulsion. Water is scattered in the form of smooth globules in the continuous diesel fuel phase into any water/diesel emulsion of fuel of practical importance relevance. This sort of emulsion is referred frequently to as emulsion of "water-in-fuel", diagrammatically depicted in Figure 1. On the contrary set-up, water will have a greater chance of contacting the cylinder liner face and other metal components in the continuous water phase, which leads to phenomena causing corrosion and engine issues.

Among various water supplements, Emulsions differentiate themselves by introducing water directly into the combustion flame region, where the emissions are generated, when the fuel spray droplets themselves are integrated. In addition to the advantage of NOx, the emulsions result in increased fuel atomization and blending, which are principally due to the decreasing burning temperature by water in all techniques [28]. Enhanced mixing, which spreads across the whole flame, can reduce PM emissions pretty impressively. Thus, water-fuel emulsions are one of the singular techniques for controlling emissions that at the same time may reduce NOx emissions and particulate emissions, without or with just a modest fuel efficiency penalty. NOx reduction emissions by emulsions have been researched more thoroughly than the reduction PM emissions. However, as will be stated later, PM decrease appears to be almost double the amount of NOx reduction to be attainable [29][30].

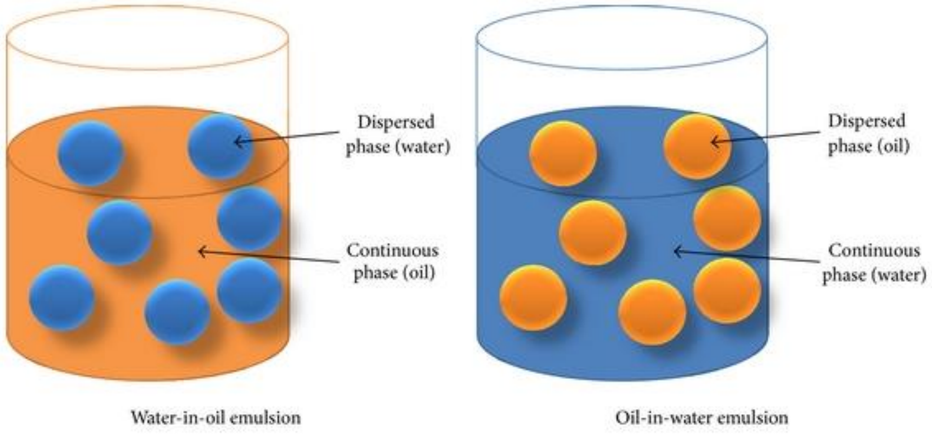

Figure 1. Two-phase water-in-oil and oil-in- water emulsions [31]

In order to emulsify significant volumes of water (up to 50%) into distillate fuels, a sufficient emulsifier is required, while yet permitting safe and dependable operation and a fuel phase homogenous emulsified water droplet mix [32][33]. Some information sources claim that the potential of NOx reduction able to up to 50% [34][35], but some other sources claim that the reduction of NOx at a maximum is only 15–25% [36][37]. Large space and time scale combustion processes are specifics of the combustion process in marine diesel engines vessel with low-speed two-strokes. Topical maximum combustion temperature reduction is one of the most effective for reducing NOx emissions. According to the research of Liu et al.[38], in order to discover the potential of the Miller cycle, multidimensional numerical simulations have been performed, in the low-speed two-stroke marine engine, EGR (Exhaust Gas Recirculation) and WEF (water emulsified fuel) combined with a high compression ratio for improving the balanced relationship between NOx-ISFC (indicated specific fuel consumption). In order to satisfy the Tier III emission condition, the result of the combination between the EGR ratio can be reduced with WEF is shown. The Miller cycle and high geometric compression ratio can assist in settling down the punishment about fuel utilized level with EGR and WEF [39][40]. By combining 20 percent EGR, 40 percent W/F (water-to-fuel ratio), and delayed exhaust valve closing timing (20°CA later), NOx emissions may be lowered by 81.1% without punishment for saving fuel, allowing Tier III emissions to be met.

During combustion, strong latent heat absorption by water particles lowers the regional high temperature, resulting in a decrease in NOx. With the W/D emulsion fuel, the NOx formation is reduced significantly, and the results are reported in all the researches. In studies of Suresh and Amirthagadeswaran [41], they have recorded that the NOx emission reduced 35% off, while 25% and 20% is the NOx reduction has been recorded respectively the studies of Ithnin et al.[42] and Ismael et al.[43]. With heat dissipation effect of fuel emulsion will decrease the burning temperature, it leads to form the low-level NOx, this is reported by Ayhan [44]. The inclusion of water in emulsion fuel causes an increase in hydroxyl (OH) content, which reduces NOx emissions. For every 10%, the water concentration in the emulsion can reduce 20% the emission of NOx is published in the numerical study of Sarvi, Kilpinen, and Zevenhoven [45]. Because the lower peak fire temperature during combustion when utilizing W/D emulsion fuel will reduce NOx emissions [16].

The key causes create the CO and unburnt HC formation in the diesel engines are soot burns slowly due to incomplete combustion, inconsistency. Because the lower combustion temperature in emulsion fuel combustion is insufficient to convert CO to CO_2, it leads to the increase of emission of CO and HC with W/D emulsion fuel [46][47], this is studied in many kinds of research. Koc and Abdullah [48] have observed and found the cause better oxidation of carbon to CO, that is the high quantities of OH contribution leading to the rise in CO and HC in emulsion fuel. One more reason that makes the CO and HC emission increase significantly is the rise in the delay of ignition, and the low flame temperature of emulsion fuel. Cui et al. [49] observed and found that the micro-explosion may lead to complete fire, this helps to reduce the emissions.

Choi and Lee [21], utilized experimental, numerical analyses and computational studies for discovering the exhaust gas identities of marine diesel oil (MDO) and fuels of emulsion, which are currently utilized to alleviate nitrogen oxides and particulate matter produced from ship engines. The humidity in the emulsion fuel predominantly enhances atomization of fuel via microexplosion, and it reduces the combustion temperature owing to evaporation latent heat from the humidity evaporation process, so, nitrous oxide and particulate matter are reduced. The reduction ratio of nitrogen oxide and black carbon is about 60% and 15% respectively in condition emulsion fuel including 16% water concentration and combustion temperature is fallen. The approach presented is a technology for controlling the burning of nitrogen oxides and reduce particulate matter by use of emulsion fuel [50].

The testing requests some water concentration modification emulsifier with 10%, 15%, and 20%, according to Cahyono et al.[51]. The performance and NOx emissions in these various water variations are extremely impactful. With a 10% emulsion of water fuel in SFOC, 216.2 g/kwh or 11.6% has increased compared to Pertamina Dex fuel. Notwithstanding, the water used for fuel emulsion in SFOC has grown by 15 percent and 20 percent to 10 percent. The decrease in NOx emissions is the effect of utilizing in the emulsion of fuel. Water has decreased by 50.5% in emulsion fuel. Generally, in order to the meet Tier 3 specification of the IMO rules, the emissions of diesel engines utilizing water in the emulsion of fuel have been enhanced significantly.

Emissions reduction via ship emulsion fuels has been investigated by Oh et al.[52], in this study, before smoke decisions were established, nitrous oxide and smoke may be reduced simultaneously in ship engines. By using a 400-kW generator motor, the combustion and emission identities are studied following the humidity concentration of the emulsion fuel [53]. The micro explosion phenomenon rises and the fire period reduces when the water concentration of the emulsion and the temperature of the fire chamber grow up. The amount of nitrogen oxide and smoke produced by the emulsion fuel used in this research is 7% and 75%, respectively. The micro-explosion of water included in the fuel during combustion motivated the reductions in nitrogen oxides and soot achieved by utilizing emulsion fuel. The nitrous oxide emissions and exhaust fumes will be fallen when the water concentration of emulsion fuel increases [54]. When the humidity of MDO grows up, smoke density and emissions will also be reduced. The following variables may contribute to the decrease of smoke with water concentration rises:(1) the combustion temperature decreased, (2) As the face region of the droplet rises owing to the micro-explosion of the emulsion, the combination of ambient air and fuel is increased; (3) The humidity has risen; and (4) water and carbon has been impacted by the aqueous interaction.

INTAKE AIR HUMIDIFICATION – HUMID AIR MOTOR

In all of the methods for reducing effectively the NOx, induct water into the smelly intake air is the simplest wet method, but it is the least effective. Especially, lubricating oil membrane and corrosion problems will occur if water is not volatilized completely, which leads to the liquid water drop may touch the cylinder septum [55]. As a result, vaporized water injection rather than liquid water could be considered, with the process of evaporation perhaps utilizing the engine's exhaust gas heat; notwithstanding, this is not particularly useful for configurational heat availability waste heat recovery [56][57].

Waste heat recovery may be beneficial in the effort to enhance the efficiency of heavy-duty vehicle engines. Technologicalheat recovery is a process that improves efficiency and reduces emissions via the evaporative cycle. A humid air motor (HAM) utilizes the waste heat from the engine exhaust to humidify the intake air, due to the increased specific heat of the humid air, leading to the NOx emission is reduced to a larger degree [25][58]. Even while the improved efficiency of the humid air motor is an advantage in the emission reduction, it is still not specifically mentioned in any literature whether there is an increase or fall in the efficiency of the humid air engine comparing to traditional engine [59]. According to Arunachalam et al.[60], a system model simulation with a 13-liter heavy-duty Volvo motor equipped is performed in order to study the effectiveness of HAM. In order to construct system models and conduct simulations, a model must be constructed and it is called GT-SUITE software, and this is commercial software. The increase in vapor mass flow generated caused a consequence of humidification contributes to the improved efficiency of the HAM. Additionally, an attempt is made to comprehend the connection between the humidified engine's efficiency and its productivity [61].

The development of combustion and high-speed marine diesel engine emission technology is essential to meet the increasingly severe requirements for emissions reduction. One of the methods for pollution controlling from diesel engines and enhance the diesel engines combustion is combustion process enriches oxygen and humidifies the intake air. CFD (Computational Fluid Dynamics) model [62] has been utilized for researching the combustion and emission characteristics of a hydraulic cooled turbocharger marine diesel engine with humidity ratio and intake oxygen content according to [55][63]. AVL Fire code established the model of combustion. At 1350 rpm, partial load bearing has been optimized utilizing a combined approach to the humidification of intake air and oxygen-enriched combustion. The simulation results show that with maintained constant the humidity ratio, when oxygen content increases, in-cylinder temperature and pressure both rise, while temperatures and peak pressures in the cylinder are raised, the length of the combustion process was brief, and CA50 is procrastinated. Although the emission of NOx increase significantly, emissions of soot are limited. In order to reduce NOx emission, humidifying the inlet air is an effective method, the advantage of this method is little effect on the amount of soot and the power specified. Both combustion pressure in the cylinder, temperature and NOx emissions are all reduced while the humidity ratio increasing. The ignition latency went increased suddenly. The results show that for creating the lower emissions of Soot-NOx than the traditional engine with the specified power loss, not excess 3%, the ratio of humidity from 60% to 80% and oxygen content from 22% to 23% is able to suitable [64].

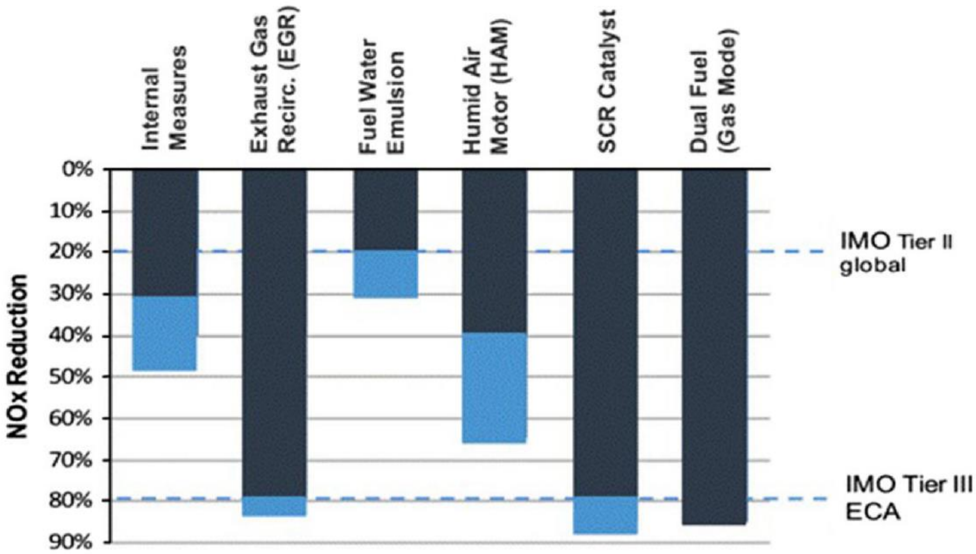

Figure 2. Comparison of NOx reduction using different technologies [65]

For the primary propulsion marine engines, the humid air engine is a technique that uses water-saturated filter air. The HAM is based on the canon that the charge air added to water lowers the release of NOx to the air by 60-80% [66]. Maximum reduction of NOx up to 65% depending on operating conditions following the experience of the MAN [67][68]. A basic issue in the concrete condition that has to increase sweep air temperature to 60–70 degrees C leading to the increase in specific fuel oil consumption, this is necessary for the condition of the amount of water in the growing of swept air. The reduction of NOx has effective up to 50–60 % throughout the regular engine running, the temperatures of scavenged air reached the required level. In Figure 2, wet technologies do well when it comes to the IMO Tier II and Tier III regulations outside the ECA. For the IMO Tier III regulation inside the ECA, it is currently widely accepted that the future major countermeasures against the NOx emission are the EGR or SCR [69].

DIRECT WATER INJECTION

Another method in the group of wet technologies is direct water injection (DWI). During travel and low motor load, capable of providing a large several of water without affecting the combustion in the cylinder and timing control, and the amount of water injected to collect NOx optimization reduce emissions are advantages of the method. In the system of DWI, the fuel-to-water volume ratio may be less than 1:1. The kind of motor is an element, that water supplied under very high pressure is dependent this element. High-pressure pump parts create high water pressure. In order to sustainable water provide to the high-pressure pumps, a low-pressure pump unit is mandatory [70].

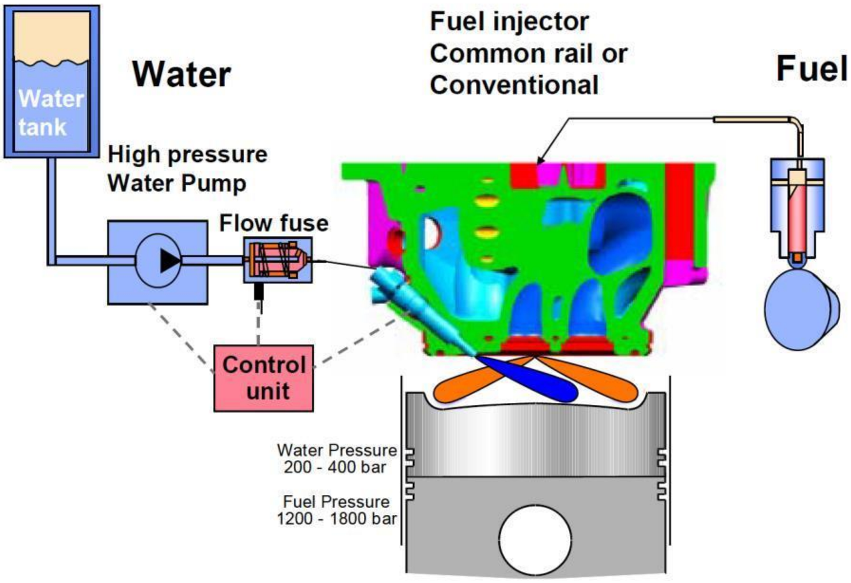

Figure 3. Direct Water Injection Concept & NOx Reduction Effects [71]

So as to reduce the emission of NOx in marine engines, Wartsila performed research including the application of this technology, in **Figure 3**. The injector has a nozzle with two needles as a special design about cylinder heads in engines of Wartsila that utilized in this research [24][72]. In order to guarantee the relevant strength and stiffness, the heads of the cylinder are created from a special stainless-steel alloy. Because the corrosive ability of water is high, the pistons and piston skirts are also created from alloys for assuring corrosion resistance. The cause that the solution is not widely popular due to operating problems. Before this FWE technology is adopted as a commercial motor, the DWI may not be used as a substitute for the FEW [73].

A further method for reducing NOx is to inject water into the cylinder. Its basic idea is to reduce peak temperatures, thus reducing NOx production. There are many methods for introducing water. Humidify intake air, inject emulsion of water–fuel, and inject directly water are three of these options. Each strategy has its own set of benefits and drawbacks. Although it is often effective at reducing NOx, it introduces certain technical challenges and sometimes results in fuel excess usage and soot emission punishment. This method has been studied by many researchers and may be utilized in compression ignition (CI) and spark ignition (SI) internal combustion motors. A detailed investigation of biodiesel injection methods for CI engines was completed by Prabhu and Venkata Ramanan [74]. With the concomitant decrease of particulate matter emissions, water injection systems may decrease emissions of NOx by up to 37–50%. Water injection has the adverse consequence of increasing emissions of HC and CO as well as specific fuel consumption in such engines. Enfrin, Dumée, and Lee [75] conducted a comparison of several water/steam injection schemes in research for fuel usage reduction in a turbo-compound diesel motor. The water evaporation phenomenon has caused fuel consumption to not be reduced, which results in a liquid water injection at the intake or in the cylinder is meaningless. The temperatures in-cylinder was fallen by the water evaporation phenomenon, resulting in a delay in the ignition and decreased in-cylinder pressure. It is possible that fuel consumption may be reduced by 10% at 1300 rpm using in-cylinder steam injection.

Water and steam direct injection is efficient in lowering pollutants and improving engine power by utilizing waste heat recovery, according to research conducted by[70], At the compression stroke, the impacts of injection of water and injection of steam on braking power and emissions in marine engines were studied, containing injection time, volume and temperature. The findings indicated that NOx emissions were decreased significantly when the injection of water technique was utilized. However, braking power was reduced as well. Not only did the SI technique reduce NOx emissions, but it also increased braking power. NOx emissions increased as the temperature increased and the time of injecting water was delayed. The adversative model was discovered for the steam injection technique. Comparing to temperature and timing, the injected volume has more impact than the power and emissions. When 20 g of water was pumped into the cylinder at 50 °CA, 15 bar, and 400 K, NOx emissions may be decreased by 72.8% but only spending a 2.08 % power. The same volume of superheated vapor with a temperature of 500 K is injected into the cylinder will help the emissions of NOx reduced up to 38.9% with a

24.7% improvement in capacity. The growing up the wattage while decreasing fuel usage and emissions may be implemented in the SI technique.

CONCLUSION

Addition of water to the diesel process decreases combustion temperatures and lowers NOx emissions. The most common methods of introducing water are direct injection into the cylinder, a process commercialized in certain marine and stationary diesel engines, and water-in-fuel emulsions. Emulsified fuels, due to increased mixing in the diesel diffusion flame, can be also effective in simultaneous reduction of PM and NOx emissions. Owing to the DWI into the combustion chamber, it is possible to reduce NOx by 40–60 %; however, it requires significant changes in the engine construction and is costly so it is more profitable for new engines under the condition of conducting further research. The HAM effectively reduces the NOx emission by 50–60 %. Apart from relatively high costs of its installation, it seems a good solution if significant NOx reduction is expected. Small changes in the engine construction support the use of this system. In all calculations the approximate producer prices of valves and pipelines were taken into account. Injecting water with the scavenging air into the combustion chamber seems to be less effective in reducing the NOx emission for two-stroke engines for there is a risk of water drops transportation through the cylinder liner inlet ports and flushing the oil film layer off, and of increasing high-temperature corrosion intensity. Supplying water with fuel seems to be the most appropriate solution for two-stroke engines.

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