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Effect of Introduction of Water into Combustion Chamber of Diesel Engines – A Review

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Abstract Introduction of water vapours directly or indirectly into the combustion chamber, is one of the effective and most economical tool in reducing oxides of nitrogen (NOx) and particulate matter (PM) in the exhaust gases of diesel engines. Many researchers have developed different systems to introduce water into the combustion chamber like direct water injection, fumigation and water-fuel emulsion. All the different systems have started during the early days of development of aircraft piston engines and since then a significant progress has been made to develop an optimum system to reduce the pollutants from the exhaust gases. This review paper presents both advantages and disadvantages of different water introduction systems achieved by the most recent studies. Also it covers the different features, main findings and theoretical and experimental approaches for water-diesel emulsion and direct water injection for DI diesel engine for further emission reduction.

Keywords Diesel Engine, Emission Control, NOx Reduction, Water Injection

1. Introduction

Diesel engines are dominating in areas restricted to agriculture, mass transportation and industries due to their high thermal efficiency and low fuel consumption compared to other engines. The facts like low specific power outputs, noisy operation, high initial cost and high emissions are making diesel engines vulnerable to passenger vehicle market. These problems in the diesel engines have been addressed to a large extent except the emission from exhaust gases. From diesel engines nitrogen oxides (NOx), particulate matters (PM), sulphur oxides (SOx), unburned hydrocarbon (HC), black smoke, carbon monoxide (CO), and carbon dioxide (CO_2) [1] are the key pollutants. Increasing market demand and stringent government regulations are pushing engine manufacturers to develop low emission diesel engines. Most of the problems have been resolved with the exception of emission levels of NOx and PM. Formation of NOx and PM are highly temperature dependent and are contradictory to each other. Attempt to reduce one will cause an increase in the other. Emission regulations in Developed countries are becoming very strict soeven trade-off strategies to reduce both pollutants are no longer adequate. One way to simultaneously reduce NOx and PM emissions significantly is to introduce water into the combustion chamber of the engine. The main mechanism causing the reduction in NOx emissions seems to be the decrease in temperature of the combustion products as a result of vaporization of the liquid water and consequent dilution of the gas phase species [2]. As for PM emissions, the presence of water during the intensive formation of soot seems to reduce the rate of formation of soot particles and enhance their burnout by increased concentration of oxidation species such as OH [3].

Water injection to the combustion chamber of a diesel engine starts much before the World War II. Many reported the use of water and water-alcohol injection on aircraft engines as thrust boosters or as power supplements during take off and also as coolant to the engine increasing the engine performance [2, 3]. Later when the pollution regulations became more and more stringent, researchers started using water injection for the purpose of reducing emissions. Nicholls et al. [4] studied theoretical and experimental analysis of injection of water to engine manifold for the reduction of NOx. The author's theoretical studies were based on the chemical equilibrium calculations during combustion peak temperature. They have used water injection during suction, compression and combustion processes. Theoretical calculations were well matched with the experimental values, reporting up to 90% reduction in NOx.

There are several ways found to introduce water into the combustion chamber of an engine. Emulsion, fumigation, and direct water injection are few effective realizations with

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their own advantages and drawbacks. (a) Fumigation is where liquid water is injected into the inlet manifold during suction stroke of the engine. (b) Fuel and water are blended using surfactants to form an emulsion which can be used as an alternative fuel. (c) Direct water injection system carries a dual feed injection nozzle with corresponding water supply system. All the water introduction methods have shown noticeable reduction in NOx and PM emissions from diesel engine. Unlike emulsified fuels, fumigation, and direct water injection allow the fuel water percentage to be changed for transient engine running conditions [6]. On the contrary no major modification in the engine is required for the use of emulsified fuels.

2. Water – Diesel Emulsion

An emulsion is a mixture of two or more liquids immiscible in nature, one present as droplet, or distributed throughout the other, in dispersed/continuous phase [7]. It is generated by means of a mechanical agitation in the presence of surface active agents, called emulsifiers or surfactants, for stability.

The fact that emulsion is used as a fuel in diesel engine, it is recommended that it should be stable and this can be realized with the help of suitable surfactants. Surfactants should easily burn with no soot and free of sulphur and nitrogen [8]. There have been a limited literature about the effect of surfactant on the characteristics of water-in-diesel emulsion as far as combustion and emissions are concerned [9]. Nadeem et al. [10] have studied water-in-diesel emulsion with conventional (sorbitanmonooleate) and gemini surfactants. They have studied the emissions by fuelling it in a four stroke and four cylinder engine test bed and concluded that for 15% water content, there is 71% reduction in PM emission with gemini surfactant water in diesel emulsion fuel.

2.1. Theoretical Advances

Theoretically the combustion process of water in diesel emulsion has been explained by many researchers. Water gets entrenched into the diesel fuel with the help of surfactants. When the emulsified fuel gets into the combustion chamber, heat transfer takes place to different fluids of supplied emulsion at different stages. Since the boiling point of water is less than the diesel, the water molecules reach their superheated stage faster than the diesel producing a vapour expansions breakup [18, 19, 20, 21]. This is the stage where the two phenomena, micro-explosion and puffing, prevail [11]. Micro-explosion is that the whole droplet breaks up into small droplets quickly, while in puffing, water leaves the droplet in a very fine mist (a part of the droplet breakup) [12, 13, 15, 17]. These micro-explosions helps in faster fuel breakdown, allowing them for secondary atomization, resulting in better mixing of air and fuel [16]. So it is important to know the basics of micro-explosion and its influencing parameters in the combustion improvements.

Fu et al. [3] have stated water in diesel emulsion can micro-explode at certain conditions only. Through a physical model, they have stated that the strength of micro-explosion is mainly depending on the diameter of the dispersed liquid present in the emulsion. Further Morozumi and saito [14] explained the importance of volatility of base fuel, type of emulsion and water content in the mechanism of micro-explosion. Also they have concluded that the increase in the emulsifier content increases the micro-explosion temperature and waiting time.

Micro-explosion is an important phenomenon in the secondary atomization process of water-in-diesel emulsion fuels. Generally, this phenomenon is depending on the diameter of the dispersed liquid, location of the dispersed liquid and ambient conditions like pressure and temperature. Although many studies have been conducted both experimentally and numerically to understand the phenomenon of micro-explosion, yet the study of its effects inside the combustion chamber are quite few. It is believed that fuel injection and the passage of emulsified fuel through the narrow exit of the injection nozzle affect the dispersed liquid behaviour of the fuel. It is therefore very important to study the micro-explosion phenomenon inside a combustion chamber and its effect on the combustion process like the secondary atomization, spray penetration, evaporation, and mixture ignition [18].

Ghojel et al. [5] investigated the process of heat release using a water-diesel emulsion, which also called as diesel oil emulsion (DOE), in a direct injection diesel engine. A heat release model has been developed for the purpose of finding specific fuel consumption using DOE. They came to the conclusion that the specific fuel consumption of DOE increased by up to 26%. Also the presence of water in the emulsified fuel decreased the temperature during the combustion process, which leads to reduction in NOx emissions. The decrease in pressure and temperature with the emulsified fuel is due to the shift of the combustion process to the expansion stroke as a result of retarded start of combustion and quenching of the combustion process by the water in the fuel. However, the reduction in the burning rate is not as great as was expected due, possibly, to the higher fuel injection rate, which improves the air fuel mixing process and accelerates the combustion process. The heat release characteristics also show that the burning rate during the diffusion phase is almost the same for both fuels despite the late start of combustion of the DOE. This is why the heat-to-work conversion efficiencies (both indicated and brake) remain almost unchanged when the engine is switched to DOE.

Samec et al. [22] presented numerical-investigations, which consist of water in diesel emulsion fuel combustion computer model as well as simulation of water in diesel emulsion injection processes. The model employed the extended Zeldovich mechanism for calculation of NOx emission with assumption that NO formation exclusively depends on oxygen atoms concentration. The reduction in NOx is therefore a consequence of the dominance of the reaction of excess watervapor with oxygen atoms rather than the reaction of N2 with oxygen atoms. Furthermore, Kannan and Udaykumar [23] have mathematically modelled nitric oxide formation in single cylinder direct injection diesel engine using diesel-water emulsion. Based on their results, it was found that 18% and 21.5% of reduction in NO was achieved with 10% and 20% dilution of diesel with water, respectively.

2.2. Experimental Advances

Experimental studies show that reduction in emission parameters specially on NOx and PM using emulsified fuel meet the emission regulations. Abu zaid [24] has studied torque, power, BSFC and brake thermal efficiency by increasing the percentage of water by volume from 0 to 20 with 5% resolution. He reported at 20% water in emulsion brake thermal efficiency increased by 3.5%.He also concluded that engine power increase with an increase in the percentage of water. On the other hand Madeem et al. [10] have reported infinitesimal difference with the power output of the engine in the speed less than 4000rpm.Even at 4000rpm, pure diesel exhibited better power output compared to all engine emulsified fuels. A power loss of 7-8% was reported by Barnes et al [25] on their application of water in diesel emulsion with 10% water content.

A similar picture can be seen in the pollutant formation. Samec et al. [22] used 10 and 15% water emulsions by volume for their experiments and showed that a reduction in HC of 52% was achieved for 10% emulsion whereas the reduction decreased to 33% when using 15% emulsion. Also Barnaud et al. [26] investigation showed a small reduction in HC (12%) with 13% emulsion by weight.

Furthermore, Kannan and Udaykumar [23] have reported that 10% and 25% reduction in NOx in a single cylinder diesel engine for 10% and 20% water in the emulsion was observed.

The situation reveals the need of further investigations of the combustion processes of water in diesel emulsion. The application of new methods of observing, such as laser diagnostics techniques, may help to better understand in-cylinder processes of water in diesel emulsion combustion, which could lead to establishment ofmore precise models of emission formation.

3. Fumigation (Inlet Manifold Water Injection Method)

At present this method is widely used in large marine diesel engines. This method may be the easier way to supply water to the combustion chamber of diesel engine without major modifications. The main advantage of this system is its simplicity and ease with which it can be integrated within the existing engines. Also advantages like uniform on-line variation of water quantity, increase of volumetric efficiency due to cooling effect, nearly or homogeneous water distribution in combustion chamber, no alter in fuel property etc. make fumigation system more interesting system to study in reducing tail pipe emissions from diesel engines. Many researchers have used different methods to inject water into the inlet air: multipoint water injection in the intake pipes close to the inlet valves and single point water injection upstream the compressor or downstream the compressor [27].The main weakness of fumigation is that the quantity of water required to reduce a significant NOx is very large when compared to water in diesel emulsion system. A water mass of about 60-65% of the fuel is needed for achieving 50% NO reduction. [28, 30]

Subramanian compared water in diesel emulsion with timed water injection to intake manifold to a 1500 rpm running diesel engine. His investigation was fixed to Water-to-diesel fuel ratio for emulsion and water injection methods as 0.4:1 (by mass). He concluded that both methods were capable of reducing NO emission drastically. However, CO and HC levels were higher for water emulsion than for water injection. Peak pressure, ignition delay and maximum rate of pressure rise were lesser for water injection compared to emulsion method [29].

Zehra Sahin et al. [27] experimentally studied the effects of water injection (WI) into intake air on the performance and exhaust emissions in a Renault K9K 700 type turbocharged common-rail DI diesel engine. Experiments were performed at different loads and engine speeds, with various water ratios. The water was injected at approximately 2%, 4%, 6%, 8% and 10% (by vol.) into intake air by a carburetor. Smoke index K decreases by increasing water ratios at 2000, 2500 and 3000 rpm. Its maximum reduction ratio was obtained as 41.75% for 11.71% water ratios at 3000 rpm. More significant reduction of NOx has been obtained after 6% water ratios. They have concluded that water injection to intake air does not show any significant change in cylinder pressure and indicated power.

Görkem Kökkülünk et al. [31] injected steam into the intake air very close to the inlet valve. They found improvements in torque, effective power, efficiency and SFC with steam injection and decrease in NO emissions significantly. At 1200rpm they determined 2.5% improvement in torque and power. At the same time minimum SFC and maximum effective efficiency are obtained at 1600 rpm. The highest change as a standard value of SFC and effective efficiency were at 2400 rpm. The minimum NO emission value was determined at 2400 rpm. Consequently, steam injection yields positive effect on performance and NO emissions at all speeds. They mentioned that steam injection does not affect CO and HC emissions considerably.

Tesfa et al. [28] investigated the effect of inlet water injection in a biodiesel engine. They conducted their experimental study in a four-cylinder, four-stroke, direct injection turbocharged diesel engine. They reported that water injection at a rate of 3 kg/h resulted in the reduction of NOx emission by about 50% without causing any significant change in the BSFC. Also, this study showed that the water injection in the intake manifold under different operating conditions had little effect on the in-cylinder pressure and heat release rate of the diesel engine.

Use of fumigation system to reduce emission has given positive results. An intensive work on theoretical model will give more input to the different parameter of fumigation like location of injector, pressure, quantity, temperature of water to be injected to get better results in performance and emission.

4. Direct Water Injection

The in-cylinder direct water injection method is also attracting attention from the use of water-diesel emulsion and fumigation, for the purpose of reducing NOx and PM [32].

One of the disadvantages of the water-diesel emulsion technique is that the water percentage cannot be changed under transient engine conditions (e.g. at cold start or changing load) compared to fumigation and direct water injection system. Similarly the disadvantage of the fumigation technique over direct injection system is that the water cannot be injected at the end of compression stroke along the fuel. So direct water injection system will have more degree of freedom compared to both emulsion and fumigation systems. Addition cost on modification of the injector make this system less popular compared to other two systems. The key to the direct water injection system is the dual feed injection nozzle with the corresponding water supply system. Here the water supply system does not support high pressure like the fuel injection system. The water and diesel mixed in the injector tip such that initial portion of the injected diesel contained mostly diesel [6]. However having water towards the front of the injection may cause ignition delay.

Bedford et al. [6] in their investigation used CFD to find the effect of direct water injection on diesel engine combustion. The simulation and experimental results indicated that the lower peak temperature in the combustion region was the cause for the lower NOx and PM emissions. The investigations also showed that, advancing the injection timing lead to significant decrease in specific fuel consumption, NOx and PM emissions at 44% load. At 86% loads large decrease in NOx and PM were observed but with small increase in fuel consumption. They used a CFD model based on a modified version of KIVA-3v to simulate the direct water injection "stratified" injector. The model used the Wolfer type equation for ignition delay calculation.

Christopher J. Chadwell et al. [33] developed a real time water injection system and applied to a heavy duty diesel engine. Using real time water injection system alone, NOx emissions were reduced by 42%. Use of EGR with real time water injection increased the reduction of NOx to 82%. They concluded that using water injection system substantial decrease in NOx, PM and CO emissions were found during steady state operation. At high loads, best performance of real time water injection system was demonstrated when the water injection was equal to 30% of the diesel injection.

Kohketsu et al. [34] used a modified injector which employed a modified water supply system together with the fuel pump system. The fuel injector was modified so that it could inject also water. The fuel and water supply systems were designed in such a way that fuel and water layers could be stratified in the injection nozzle. During injection, water and fuel are successively injected into the combustion chamber. They conducted tests in a typical engine of an urban bus under medium and high load conditions. The results were highly promising. NOx concentration in the exhaust gases decreased almost linearly with increase in water/fuel ratio. The reduction of NOx was nearly one-to-one with the volumetric content in the total injected fuel. The study also confirmed the hypothesis that NOx reduction is caused by reduced flame temperature.

5. Conclusions

The use of water in the combustion process of internal combustion diesel engine can be a part of solution to the problem of pollution control and fossil fuel depletion. Using water-diesel emulsion, NOx and PM emissions can be effectively controlled inthe diesel engines. The mechanism of micro-explosion of the droplets is understood from theoretical view to a certain extent. Many mathematical models are also formulated to understand the concept of micro-explosion in water-diesel emulsion and have been verified experimentally. A number of computer models have been built to predict heat release rate, pollutant emission concentrations in the exhaust gases as well as spray penetration and spray angle.

Experimental investigations confirm the advantages of water in diesel emulsion technique in reducing NOx and PM emissions, but some studies also reveal the trade-off between NOx-PM and CO-HC emissions, which requires further studies to understand the problem and find the solution for it.

Beside the water-diesel emulsion technique, the fumigation has also been investigated. The available results show a significant reduction of NOx and PM emissions in the system using the method. Compared to emulsion a less number of studies are followed in fumigation. A mathematical model and the better understanding of the mechanism of fumigation will overtake the popularity of emulsion systems. Both emission and Performance parameters are not extensively studied to the required stage.

The direct water injection method has also been investigated to emission and performance parameters of the diesel engine. Results show a significant reduction of NOx and PM emissions in the system using the method. The cost of engine conversion is still remaining the main obstacle to its wide application in practice.

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