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# Effect of Water Injection into Exhaust Manifold on Diesel Engine Combustion and Emissions

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**Abstract**

In this study, an experimental investigation was conducted to assess the combustion and emissions of a single cylinder diesel engine using water injection in the exhaust manifold. Water is injected into the exhaust manifold and by opening the exhaust valve during the intake stroke, the injected water, and exhaust gases are reentered the engine cylinder then mixed during the intake and compression stroke and participated in the combustion process. The purpose of this injection strategy is to utilize the exhaust gases enthalpy to evaporate water before combustion to reduce soot and $NO_x$ emissions without decrease combustion temperature. The results show that water injection leads to increase in the cylinder pressure, apparent heat release rate (AHRR) in premixed combustion phase and, the ignition delay comparing with EGR without water injection. The indicated mean effective pressure (IMEP) for EGR without water injection is lower than conventional diesel combustion with 14 %. However, with water injection, the IMEP increased with 11% comparing to EGR without water injection. $NO_x$ emissions reduced up to 85% comparing to conventional diesel combustion due to the EGR effect. Soot concentration increased dramatically with EGR. However, with water injection, soot emissions reduced by up to 40% but still higher than conventional diesel combustion.


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*Keywords:* Diesel Engine; Water injection; Combustion control; Emissions; Exhaust gas recirculation

**Nomenclature**

| | | | |
|---|---|---|---|
| AHRR | Apparent Heat release rate | IVC | Intake Valve Close |
| ATDC | After Top Dead Center | IVO | Intake Valve Open |

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|---|---|---|---|
| BDC | Bottom Dead Center | $NO_x$ | Nitrogen Oxides |
| CO | Carbon Monoxide | OH | Hydroxyl group |
| EGR | Exhaust Gas Recirculation | PM | Particulate Matter |
| EVC | Exhaust Valve Close | Ppm | Part Per Million |
| EVO | Exhaust Valve Open | SOI | Start of Injection |
| FPGA | Field Programmable Gate Array | VVA | Variable Valve Actuating |
| HC | Hydrocarbon | WI | water injection |
| IMEP | Indicate Mean Effective Pressure | | |

## 1. Introduction

Diesel engines are widely used in transportation systems and power generation and play a major role in influencing fuel economy as well as contribute to the environmental impact of air pollution significantly. Nitrogen oxides $NO_x$ and soot are the predominant pollutants from diesel engines. Additionally, Growing concerns about fossil fuel depletion and recent tendency towards more strict regulations on emissions have been a significant incentive for improving the fuel efficiency and reducing in-cylinder emissions. Water injection is one of the used in-cylinder strategies aiming to control the diesel combustion and emissions and has studied for decades. Water injection has various effects on diesel combustion such as the dilution effect, the thermal effect, and the chemical effect and all of them contributed to $NO_x$ and soot reduction [1 – 12]. The decrease in soot and PM emissions with water injection was reported as a result of the dilution effect which occurs due to micro-explosions or sudden expansion caused by the disruptive effect of water vaporizing within the fuel droplets during the droplet heating period [1]. Also, the reduction of PM and soot emissions was explained due to the increase in total injected mass that increases the mixing rate between fuel and air. Consequently, the mass fraction of the fuel that burns under premixed condition increased [2]. The water thermal effect is defined as the injected water getting the latent heat of vaporization from the heat released during the combustion results in lower heat release and flame temperature. The water thermal effect is due to the high latent heat of vaporization and specific heat capacity of injected water and results in decreasing the diesel flame temperature and consequently the thermal $NO_x$ [6], [8], [9], [10], and [11]. The chemical effect was explained as the water addition leads to increase in OH radicals that might have a significant impact in soot oxidation and reduce the soot formed in the gas phase [1], [12]. However, the three effects are related as the dilution of water vapour may terminate the chemical reaction in the gas phase due to the reduced apparent heat release rate (AHRR). The suppression of the chemical reaction might cause a reduction in flame temperature and consequently a reduction of thermal $NO_x$ emissions [12].

There are three ways to introduce water into the engine cylinder. Firstly, by using water injection in the intake manifold. Secondly, by direct water injection in the engine cylinder using a separate injection pump and the injection nozzle. Also, by water injection directly into the cylinder through the fuel injection nozzle either by a separate injection pump or by water and fuel emulsion [1], [4], and [7]. Many researchers investigated the injection of water in the intake manifold. The water/fuel ratio increased up to maximum 65% [4]. They reported that water to fuel mass ratio of 60-65% is needed to obtain a 50% $NO_x$ reduction. Most studies show a decrease in $NO_x$ with a slight increase in PM emissions and increase in CO and HC emissions while increasing the water quantity that uses the in-cylinder heat release to evaporate and reduce the flame temperature [4]. Also, a decrease of in-cylinder mean pressure and burning rate reported with water injection combined with an increase in the combustion duration [6]. Additionally, Ignition delay increased with water injection which leads to a significant fraction of premixed burning, higher rates of cylinder pressure rise, and increased combustion noise [1]. This technique suffers from the drawback that the liquid water in the combustion chamber is typically in areas where it is less efficient to reduce emissions. Therefore, this method requires approximately twice the liquid volume for the same reduction in $NO_x$ comparing to direct water injection. Additionally, liquid water present after combustion can contaminate the oil and increase engine wear [7]. One advantage of in-cylinder direct water injection as compared with water/diesel emulsion is the