Assessment of atomized water injection in the intake manifold of a heavy duty diesel engine for NO\textsubscript{x} reduction potential

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Abstract. Diesel engines, since many years, have found their own market with their robustness, low manufacturing cost and high efficiency. Although diesel engines have so many advantages, they are being blamed for their high pollutant emissions. Main pollutants from diesel engine are NO\textsubscript{x}, CO, CO\textsubscript{2}, HC and PM. Out of these pollutants, CO, CO\textsubscript{2}, HC, and PM can be reduced using some after treatment system in the tail pipe. But NO\textsubscript{x} needs to be addressed within the cylinder which would reduce the cost of after treatment system. Since NO\textsubscript{x} formation is the function of high combustion temperature, this temperature should be reduced by some means. In this study, atomized water injection system was employed to reduce in-cylinder combustion temperature there by reducing NO\textsubscript{x} formation. Here, water was injected into the air-intake pipe along with the EGR stream. 1-D simulation model of the study engine was created using AVL BOOST. Three full load operating points were considered and simulations were performed for 2.8mg, 4mg and 6mg of water injection at each operating points. Performance and emission parameters were then validated with the test data. Results showed that increase in water injection quantity reduces NO\textsubscript{x} emission but increases the smoke value. 2.8mg of water injection was chosen to be optimum, which reduces about 90\% of in-cylinder temperature, 8-10\% of NO\textsubscript{x} reduction and increases smoke by about 20\% from base value.

1. Introduction
With the upcoming stringent pollutant emission regulations, reduction of nitrogen oxide (NO\textsubscript{x}) emissions will become particularly critical on automotive Diesel engines. There are different methods to reduce in-cylinder NO\textsubscript{x} formation. One among them is the Exhaust gas recirculation (EGR), in which a part of exhaust gas is channeled into the air-intake pipe. This is the most widely employed method of NO\textsubscript{x} reduction. EGR reduces the excess of oxygen available and cut down the NO\textsubscript{x} formation effectively. This reduces the in-cylinder temperature, especially in the lean side of the diffusion flame where NO\textsubscript{x} is produced. The main disadvantage of EGR is the raise in particulate matter (PM) emissions and though maintaining suitable air fuel ratio, boost pressure needs to be increased in the middle and high load operations. Another method of reducing in-cylinder peak combustion temperature and consequently the NO formation rate is the injection of water (WI). Water can either be injected into the intake manifold of an engine or directly into the cylinder as a diesel water emulsion or just water. The advantage of WI as compared with EGR is the possibility of reducing NO\textsubscript{x} at lower or higher loads without much increase in the PM. Application of water in the diesel engine is prevailing from many years. Though many researchers, academicians and engineers have studied the benefits of water injection in diesel engine,
concept can’t be seen in mass production till date. Masahiro Ishida et.al [1] in 1997 came across tremendous reduction of NO\textsubscript{x} by injecting water through the ports. They found that by injecting 0.03kg of water per every kg of air-mass, about 50% NO\textsubscript{x} can be reduced. In 2001, Breda Kegl et.al [2] investigated the effect of water injection and water-fuel emulsion on engine performance and emission parameters. In comprising several approaches of water addition, they found that the water/fuel emulsion could be most successfully employed in order to reduce truck diesel engine exhaust pollutant emissions. In 2003, R. Udaykumar et.al [3] conducted experiment by injecting water in the inlet manifold of an engine. They concluded that increase in water to fuel ratio will slightly reduce brake thermal efficiency and constant decrease in NO\textsubscript{x}. In 2014, Sagar Patel et.al [4] investigated emission and performance parameters of a single cylinder engine by introducing different quantity of water through calibrated burette. They concluded with about 46% reduction in NO\textsubscript{x} over the entire load range but HC, CO and CO\textsubscript{2} increased slightly. In 2016, M. Kettner et.al [5] carried out experimental study on 4-cylinder diesel engine to know the effect of different amounts of water on the performance and emission characteristics of the engine by developing single point water injection system. From this study, authors observed that high water injection rates have negligible effect on combustion. Recently, in 2016, Paras.B.Oza et.al [6] experimentally studied the combine effect of water injection and exhaust gas recirculation on the emission and performance parameters of single cylinder four stroke diesel engine. They found that increase in water quantity by volume will result in improved engine performance. In this paper, detailed 1-D thermodynamic simulation modelling of water injection system is explained. This involves experimental work and numerical validation of the 1-D model with experimental data. Different quantities of water were simulated and optimum quantity of water injection is suggested.

2. Experimental Set-Up

A 3-cylinder turbo-charged common rail direct injection diesel engine with EGR was used in this study. Intake air mass flow was measured using an air mass flow meter which works on the principle of hot-wire anemometer. The Air Conditioning System (ACS) can control the intake air temperature up to 70°C. A separate fuel conditioning system was used to maintain the temperature of the fuel. A NO\textsubscript{x} sensor was installed in the exhaust pipe and it was connected to INCA software to record ppm values. Smoke values were recorded using smoke meter and soot calculations were carried out.

![Figure 1. Block diagram of water injection system with injection control system.](image-url)
Figure 2. Test bed set-up for water injection study.

Figure 3. Atomized water spray from the injector.

Table 1. Test engine specifications

| Parameters            | Specifications                  |
|-----------------------|---------------------------------|
| Engine power          | 115 HP                          |
| Rated engine speed    | 2700rpm                         |
| Peak torque           | 320 Nm                          |
| No. of cylinder       | 3 cylinder, inline configuration|
| Fuel injection system | 1600bar, common rail direct injection|

2.1. Atomized Water Injection System
Water injection system consists of a water injector, water tank, a water filter, and a driver circuit for actuating water injection. Water injector used here has an inbuilt pump which can inject water up to 10 bar pressure. Water from the tank was fed to the injector through connecting hose by gravity feed mechanism. This does not require additional pump to inject water. A water filter was kept across the pipe to filter out the dust particles in order to avoid clogging of the injector holes. Water droplets as fine as 140 microns were injected into the air intake pipe, down the EGR stream which were expected to further atomize in the intake pipe pressure conditions. In the current study, injector was actuated by the driver circuit which was operated by an open Electronic control unit (ECU). This open ECU was integrated with the engine ECU. Program was fed into the ECU to inject three pulse of spray in one cycle, which means one spray to each of the cylinder. The spray quality of the injector is shown in the figure (3).

2.2. Test Procedure
Three operating points were considered for this study i.e. A100, B100 and C100. Where A100 stands for the operating speed of 1725rpm with 100% throttle, B100 stands for the operating speed of 2075rpm with 100% throttle and C100 stands for the operating speed of 2425rpm with 100% throttle. First set of data was collected for base engine, without water injection system. Engine was warmed up for 15 minutes by running it in idle mode and then slowly first operating point i.e. A100 was reached. The performance parameters like torque, power, BSFC, fuel flow, peak firing pressure (PFP) and
emission parameters like NO\textsubscript{x} values, and smoke values were recorded. Same procedure was repeated for other two modes and values were recorded. Then, exiting air-intake pipe was replaced with new air-intake pipe having water injector housed on it. A radiator tank was used for water storage at certain height to aid gravity feed to the injector through a filter. An Arduino driver was used to actuate the water injection system. 2.8mg of water was injected for every cylinder which accounts for 8.4mg/cycle.

3. Simulation Model
3.1. Simulation Model Building
Figure (4) shows the test engine circuit diagram created in AVL BOOST for the base model calibration. This simulated engine model was modeled by selecting the elements mentioned in table 2. The air from the atmosphere enters through the system boundary SB1 via air-cleaner CL1. In the air-cleaner, properties like air-cleaner volume, length of the cleaner, air inlet temperature, air-inlet pressure and target pressure drop were defined. The atmospheric boundary conditions were defined at the system boundaries 1 and 2. The air sucked in gets compressed in the compressor C. The exhaust gas from the cylinder enters the turbine T. Efficiency of the compressor determines the air mass flow rate. A part of exhaust gas was taken as EGR supply. An EGR cooler was modeled to cool down the exhaust gases. In this simulation model, 1\textsuperscript{st} law of thermodynamics is solved before and after each element. Three water injectors I1, I2 and I3 were placed along the EGR mixing pipe. This was taken to the cylinder through a plenum PL1. After turbine, exhaust gases pass through catalytic converter for maintaining backpressure after the turbine T. Experimental work involves single water injector which was programmed to inject three pulse of water every cycle but simulation model consists of three injectors. This is because in the 1-D simulation model, each injector can inject water at a particular crank angle with respect to particular cylinder i.e. 1\textsuperscript{st} injector injects water at 0\(^{0}\) CA (Crank Angle) with respect to 1\textsuperscript{st} cylinder, 2\textsuperscript{nd} injector injects water at 240\(^{0}\) CA with respect to 2\textsuperscript{nd} cylinder and 3\textsuperscript{rd} injector injects water at 480\(^{0}\) CA with respect to 3\textsuperscript{rd} cylinder. So each cylinder needs separate injector in this model. Later in the injector, local fuel i.e. water is defined.

![Figure 4. AVL engine simulation model.](image)

| Elements | Number |
|----------|--------|

Table 2. Elements used in building 1-D simulation model.
3.2. Combustion Model
The mixing controlled combustion model (MCC) was used to predict the combustion characteristics of the engine. The AVL MCC model determines the rate of heat release and NOₓ formation in DI-Diesel engines based on the availability of fuel quantity in the cylinder and on the turbulent kinetic energy introduced by the fuel injection. Number of injector holes, diameter of the injector hole, coefficient of discharge of the injector holes and rail pressure are used as an inputs to calculate with the effective hole area, velocity and thus the kinetic energy of the fuel jet [9][10].

3.3. Heat Transfer Model
AVL2000 heat transfer model was used in this study which is a modified form of Woschni model [9][10]. In this model, the diameter of the intake ports should be accurately specified as these diameters of the intake port directly at the intake valve has a special significance in this model.

3.4. Emission Formation Model
Formation of NOₓ in IC engine is calculated by a computational program based on reaction-kinetic model which was given by Pattas and Hafner. This program is based on the famous Zeldovich mechanism [9][10]. Soot formation model is based on the schubiger model. The difference between rate of soot formed and oxidized is the net rate of soot mass.

The constants considered in the Emission model are:
NOₓ Kinetic Multiplier: Parameter to tune the NOₓ production model.
Soot Production Constant: Parameter to tune the soot production.
Soot Consumption Constant: Parameter to tune the soot consumption

These three constants were optimized for all the three operating point in-order to have a correlation with testing data. These constant values for the three operating points are given in Table (3). Initially, these constants were optimized for the base engine operating modes. Later, for studying different water injection quantity, same constants were maintained and results were plotted. Physical properties defined in AVL MCC model are listed in the Table (4).

| Operating point | Speed (rpm) | NOₓ multiplier | Soot production constant |
|-----------------|-------------|----------------|-------------------------|
| A               | 1725        | 0.16           | 2300                    |
| B               | 2075        | 0.105          | 2300                    |
| C               | 2425        | 0.105          | 1700                    |

Table 3. Elements used in building 1-D simulation model.
Table 4. Elements used in building 1-D simulation model.

| Element                        | Value   |
|--------------------------------|---------|
| Number of injector holes       | 7       |
| Injector hole diameter         | 0.152   |
| Coefficient of discharge       | 0.75    |
| Rail pressure                  | A-1136  |
|                                | B-1464  |
|                                | C-1517  |

4. Results and Discussions

4.1. Model Validation

The simulated results were compared with the experimental data. Figure (5) shows the comparison between simulated ROHR and experimental ROHR at an operating speed of 1725rpm. ROHR of AVL MCC model narrows down in the diffusion phase but follows the same trend as experimental ROHR. A difference in peak of 9-10% can be seen between simulated and experimental ROHR. Figure (8) and (9) shows comparison among simulated and experimental emissions of NOx and Smoke at three considered operating points. Emission validation shows good co-relation between simulated and experimental emissions with an error difference of 3-5%.

![Figure 5. Rate of heat release and in-cylinder pressure comparison at an operating speed of 1725 rpm.](image)

4.2. Validation of Water Injection Model

Experiment was carried out by injecting 8.4mg/cycle of water in the intake pipe of an engine and same configurations were defined in the 1-D simulation model to simulate water injection. The engine performance parameters like, power, break specific fuel consumption, and emission parameters like NOx, and smoke values were compared. Figure (6) shows the comparison of experimental and simulated power for both base engine as well as water injection cases. Base experimental power was compared with the simulated power but water injection case shows power difference of 2-3kW. Since this error accounts for less than 5%, it can be considered for further evaluation.
Figure 6. Power output validation at three operating modes.

Figure 7. BSFC validation at three operating modes.

Figure (7) shows that simulated BSFC showing an error difference of about 10% from the base case. This increase in the BSFC is due to 2–4kW power difference between experimental and simulated data. However, from the test data, for 8.4mg/cycle of water injection, NO\textsubscript{x} emission reduces by 8% in A100 mode, 10.5% in B100 mode, and 9% in C100 mode is observed. On the contrary to this Smoke value increase by 26%, 22% and 21% in A100, B100 and C100 respectively. It is obvious that when water is injected, it reduces the in-cylinder temperature which corresponds to reduction in NO\textsubscript{x} emission. Water injection is suitable at high speed conditions than at lower speeds, because at lower operating speed (A100), smoke emission increases by 26%. Where as in at higher operating speed (C100), increase in smoke was comparatively lower as shown in figure (8) and figure (9).

Figure 8. These two figures have been placed side-by-side to save space. Justify the caption.

Figure 9. These two figures have been placed side-by-side to save space. Justify the caption.

4.3. Effect of Water Injection Quantity

1-D thermodynamic model was developed for simulating water injection in diesel engine using AVL BOOST. Initially the model was validated with test engine data with water injection configuration. Further, the effect of different quantities of water was studied with same simulation model. Figure (10) shows the in-cylinder pressure and ROHR comparison between different water injection quantities like 2.8 mg, 4mg and 6mg.
The temperature of intake air after inter-cooler will be 40 to 45°C. But after EGR mixing, the temperature rises to 75°C. Water injected along the EGR stream absorbs this available heat and reduces the intake charge by 8-10°C. The overall heat release is reduced because part of it is utilized in the evaporation of water particles. Due to reduced heat release rate and increased specific heat, the in-cylinder temperature reduces by 80-90°C (specific heat of moist air is greater than dry air).

Figure 12 shows comparison of Power for different quantities of water at different modes. With increase in water quantity, reduction in power can be seen which corresponds to increase in BSFC as shown in figure 13. Reduction in power is due to reduction in ROHR. Figure 14 shows the reduction in NOx formation. This is because of the reduced in-cylinder temperature. This in-Cylinder temperature reduction reduces desorption of nitrogen triple bond. Figure 15 shows increase in smoke formation. This is because of increase in unburnt hydrocarbon adsorbed on the soot core due to water injection. And also, due to comparatively low combustion temperature, rate of oxidation of soot is reduced. Though increase in water quantity gives better reduction in NOx, higher water injection quantities cannot be used as power and BSFC deteriorates. Also looking at the trade-off between NOx and smoke emissions, lower injection quantities are more beneficial. Table (5) shows the results of power, BSFC, NOx and smoke for different water quantities at different operating modes.
5. Conclusion
The main objective of this work is to reduce NO\textsubscript{x} emission from the diesel engine with atomized water injection system which was employed to reduce in-cylinder combustion temperature. The effect of water injection in the intake manifold of the diesel engine on emission and performance parameters of a multi cylinder diesel engine was studied. It was done by varying the quantity of water by considering three full load points. Experimental work have been conducted to illustrate the water injection effect by injecting 2.8mg water quantity and same has been validated by a 1-D thermodynamic simulation model developed using AVL BOOST. Further, validated simulation model was considered to study the effect of different water injection quantities like 4mg and 6mg of water. From the Results it is observed that, when the water injection quantity is increased NO\textsubscript{x} emission reduces but it increases the smoke emission. Reduction of power and BSFC was also observed at higher water injection quantities. So in order to overcome the above drawback 2.8mg of water injection was chosen to be optimum quantity, which reduces about 90\% of in-cylinder temperature, 8-10\% of NO\textsubscript{x} Reduction and increases smoke by about 20\% from base value.

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